EVALUATION OF THE MODES OF TRANSPORTING GTL PRODUCTS THROUGH THE TRANS-ALASKA PIPELINE SYSTEM (TAPS)

By

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THROUGH THE TRANS-ALASKA PIPELINE SYSTEM (TAPS)

A

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ABSTRACT

Gas-to-liquids (GTL) conversion technology, where Natural Gas is chemically converted to transportable hydrocarbon liquid products, is an emerging technology that will undoubtedly reach commercialization within the next decade. Two GTL transportation modes, that could be used to exploit vast Alaska Natural Gas resources in the form of stable liquid through the Trans-Alaska Pipeline System (TAPS), are evaluated either as single slugs (batches) or commingled (mixed) with Crude Oil.

In this study, the pertinent energy equations are solved for both batch and commingled flow modes. The solutions of these equations are analytically presented for determining among other parameters, the pressure gradient and pertinent slug length required for batching. The application of the determined hydraulic parameters will aid in the analysis and economic evaluation of the GTL transportation modes through the Trans-Alaska Pipeline System (TAPS).

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Gas-to-Liquids (GTL) conversion technology is a two-step process whereby natural gas is chemically converted to transportable hydrocarbon liquids. It is still an emerging technology that is destined to reach significant commercialization within the next decade. It has the added incentive of providing a means of harnessing and utilizing stranded gas reserves for commercial and profitable purposes.

One of the first areas in the United States to exploit this technology will be the Alaskan North Slope (ANS). The proven and recoverable reserves of conventional natural gas in the developed and undeveloped fields in the Alaskan North Slope (ANS) are estimated to be 38 trillion standard cubic feet (TCF). In addition to this, estimates of undiscovered gas reserves in the Artic fields range from 64 TCF upwards to 142 TCF. Currently, only a small portion of the produced natural gas on the North Slope of Alaska is used in oil-field operations, such as gas lift and power generation, and in local sales. The unused portion is injected back into the reservoir for pressure maintenance and oil production. It is expected that as crude oil production on the North Slope continues to decline, approximately 26 TCF of ANS natural gas will become available for gas sales, transportation, and/or conversion to GTL products.

Currently, there exist several different options for ANS gas utilization or transportation (**Sharma et al, 1988**). These include:

1. Transportation through a Trans Alaska Gas Pipeline System through Canada to the contiguous United States;

2. Transportation through a Trans Alaska Gas Pipeline System (TAGS) followed by physical conversion to liquefied natural gas (LNG) for shipping via LNG tankers to Pacific-Rim markets;
3. Chemical conversion to transportable liquid fuels via GTL technology and transportation through the existing Trans Alaska Pipeline System (TAPS);
4. Transportation to markets via natural gas hydrates (NGH) distribution system;
5. Conversion to miscible injectant (MI) on the North Slope for enhanced oil recovery (EOR) operations;
6. Conversion to methanol for vehicle fuel and feedstock to industry;
7. Local usage for electrical power generation;
8. Natural gas based petro-chemical complex.

Of the options listed above, the most promising is the conversion to GTL and transportation through the Trans Alaska Pipeline System (TAPS) (Robertson et al, 1996). With the current and steady decline in the daily throughput of crude oil through TAPS, it opens the possibility of providing the necessary volume of fluid, required to sustain pipeline operations.

For this proposal to be effective, there are a host of issues that need to be addressed. This is because TAPS was originally designed to handle only crude oil. A suitable and effective mode of transporting the GTL through the pipeline will have to be researched.

In transporting the GTL products through the TAPS, there are currently two possible modes. In the first mode, alternate batches or *slugs* of crude oil and GTL can be transported through the pipeline. This mode is referred to as batching or *slugging*. A minimum slug length will be required because some mixing between the crude oil and GTL will take place at the leading and trailing edges of the slugs. In the second mode, the liquid fuel (GTL) can be mixed with the crude oil and sent through the pipeline as a single liquid phase. This mode is termed *blending or commingling*.

The possibilities presented by GTL, has enabled it to become the focus of a 3-year comprehensive research project, in the Petroleum Engineering Department of the University of Alaska Fairbanks funded by the US Department of Energy (DOE). The focus of the project would be to evaluate the technical and economical factors that must be considered, in order to fully exploit the opportunities presented by GTL.

1.2 OBJECTIVES OF THIS STUDY

The objective of this study is to solve the pertinent energy equations for both batch and commingled flow modes, and to analytically determine the pressure gradients and related hydraulic flow parameters for each transportation mode.

CHAPTER 2

LITERATURE REVIEW

2.1 BATCH FLOW

The transport of GTL and Crude Oil in slugs or batches, results in the creation of an interface zone between both fluids. This is analogous to two-phase slug flow in pipelines, in that each batch or slug is followed by an air pocket. This interface zone is made up of mostly air pockets, and a mixture of both fluids. The magnitude of the interface zone is a function of the fluid velocity, density differences, viscosity, pipe diameter, length, time and composition (**Baum et al, 1998**).

Two-phase flow is a more complex phenomenon than single-phase flow, primarily because the distribution of the two phases is unknown and difficult to specify quantitatively. When gas and liquid flow simultaneously in a pipe, the two phases can distribute themselves in a variety of flow configurations, depending on operating parameters, physical properties of the two-phases, as well as geometrical variables (for purposes of this work, any mention or reference to "gas", is in actuality, a reference to the air pockets between slugs). In addition, the flow is affected by various factors such as the liquid hold-up, void fraction, pressure loss etc.

The fundamental flow patterns as classified by Baker (1954) are:

i) *Stratified flow*: Flow in which the liquid flows along the bottom of the pipe and the gas flows above, over a smooth liquid interface.
ii) *Wavy flow*: This is similar to stratified flow except that the gas moves at a higher velocity and the interface is disturbed by waves traveling in the direction of flow.

iii) *Slug flow*: Flow in which a wave is picked up periodically by the more rapidly moving gas, to form a frothy slug which passes through the pipe at a much greater velocity than the average liquid velocity.

iv) *Plug flow*: Flow in which alternate plugs of liquid and gas move along the upper part of the pipe.

v) *Bubble flow*: Flow in which bubbles of gas move along the upper part of the pipe at approximately the same velocity as the liquid.

vi) *Annular flow*: Flow in which the liquid forms a film around the inside wall of the pipe and the gas flows at a high velocity as a central core.

vii) *Spray flow*: Flow in which most or nearly all of the liquid is entrained as a spray by the gas.

These flow patterns have been further classified into four major types: *Stratified Flow* (Stratified Smooth and Stratified Wavy), *Intermittent Flow* (Elongated Bubble Flow and Slug Flow), *Annular Flow* (Annular Mist Flow and Annular Wavy Flow), and *Dispersed Flow* (Taitel *et al*, 1976; Aziz *et al*, 1978).

2.1.1 Slug Flow

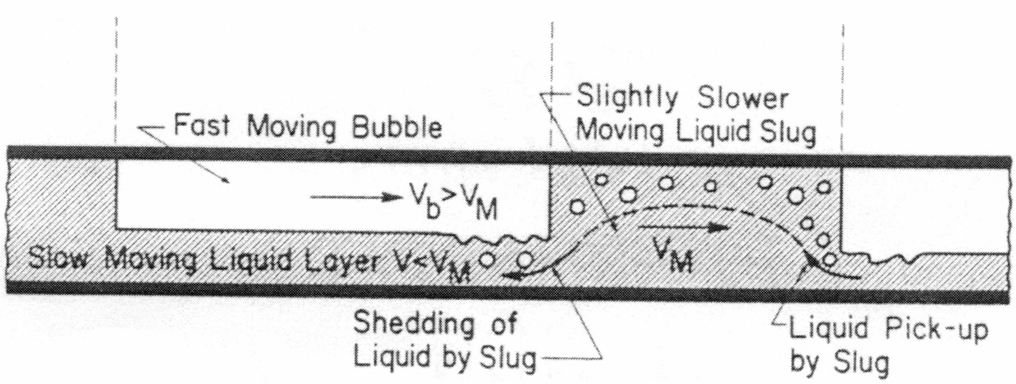
This occurs because of the velocity difference in the flow of gas and liquids. The liquid phase grows in amplitude until; it succeeds in bridging the entire cross-section of the pipe to form a "slug". The slug is immediately accelerated to an average stable velocity, by the gas behind it (Govier and Aziz, 1972).

The length of the gas bubble depends on the flow rates and the fluid properties, and for given flow rates, it depends on the manner in which the fluids are introduced. It also depends on the system pressure and therefore increases as the pressure declines in the direction of flow (Govier and Aziz, 1972).

Various models have been proposed to account or describe slug flow in horizontal pipes or tubes. Kordyban (1961) was the first to propose such a model. In his model, the liquid slug moves at the average velocity of the gas bubble and "skates" over the top of the more slowly moving liquid below it. Based upon this concept, a pressure drop expression was developed. Govier and Aziz (1972) later discovered that the model was oversimplified and inadequate.

Dukler and Hubbard (1975) presented a model that until today remains the reference point for the analysis of gas-liquid slug flow in pipes. The model permits the prediction in detail of the unsteady hydrodynamic behavior of gas-liquid slug flow. It is based on the observation that a fast moving slug overruns a slow moving liquid film, accelerating it to full slug velocity in a mixing eddy located at the front of the slug. A new film is shed behind the slug ("*scooping mechanism*") that decelerates with time.

Figure 2.1 Schematic Representation of the Dukler and Hubbard Model



The model is based on the following assumptions:

i) Steady state representation of the slug.

ii) Mixing in the slug is a result of a mixing eddy and diffusion due to turbulence.

iii) Slug length is constant.

iv) Amount of liquid scooped at the head of the liquid is equal to the amount of liquid shed at its tail.

v) Pressure drop across the film is negligible.

The model has the ability to predict the slug fluid velocity, length of the slug, film region behind the slug, film distance as a function of time and distance, as well as the pressure drop (containing an acceleration and frictional term) across the slug. In 1989, Kokal et al highlighted a shortcoming of the model, in that it requires the values of slug frequency and liquid hold-up in the liquid slug, which are difficult to estimate.

Over the years, various workers have modified the basic assumptions inherent in the Dukler and Hubbard model, and have derived new models or procedures for obtaining the parameters required for the description of slug flow.

Taitel and Dukler (1976) presented a theoretical model for the prediction of flow regime transitions in two-phase gas-liquid flow. The model also predicts the slug frequency and hold-up, parameters that are required by the Dukler and Hubbard model (1976).

Gregory et al. (1978) proposed a correlation for the estimation of the liquid volume fraction in the slug, which was an improvement over that earlier proposed by Hubbard (1965). This mechanistic model enabled the prediction of pressure drop and holdup for slug flow in pipes.

Nicholson et al. (1978) modified the Dukler and Hubbard model (1976), by incorporating empirical correlation's for the slug velocity and the in-situ liquid volume fraction (liquid hold-up) in the slug. Their work required that either the slug frequencies or slug length corresponding to the design conditions, must be known. From the results, the calculation of the average pressure gradient and in situ liquid volume fraction, are relatively insensitive to the specified conditions, and in fact, good results can be obtained by the assumption of a constant slug length.

Barnea et al. (1985) presented empirical correlations for estimating the liquid hold-up, based on the assumption that the gas in a developed liquid slug appears as a dispersed bubble. Their model has a dual capability, in that it can be used for both horizontal and vertical slug flow. It can also be used to yield the transition between elongated bubbles and slug flow within the intermittent flow pattern.

In 1986, Scott et al. studied the prediction of slug characteristics for large diameter pipes, by collecting data from flow lines in the Prudhoe Bay field of Alaska. A correlation for predicting the slug length for gas-liquid two-phase slug flow in horizontal large-diameter pipes was then developed from the results of the data acquisition. The equation has the added capability of accounting for the slug growth as it flows through the pipeline.

Kokal et al. (1989) presented a modified version of the Dukler and Hubbard model. Their model incorporates the effect of inclination in horizontal flow, and tries to account for the pressure drop across the liquid film or bubble.

Taitel et al. (1990) took into account the effect of inclination and pressure drop across the film, in their modification of the Dukler and Hubbard model.

Abdul-Majeed et al. (1996) modified the Taitel and Dukler correlation for the prediction of liquid hold-up in horizontal gas-liquid flow. The correlation predicts better results.

2.2 COMMINGLED FLOW

In this mode of transportation, the Crude Oil and GTL are blended, before being sent through the pipeline as a single liquid phase mixture. This mode is termed *blending or commingling.*

The transport of fluid mixtures in horizontal or nearly horizontal pipes has become the norm, especially in the gathering and processing of hydrocarbons. This enables major cost savings in pipeline construction, and permits the centralization of processing facilities. This usually results in the improvement of processing economics and conservation of resources.

When a mixture of fluids flows in a system, the component fluids can be distributed in a variety of flow configurations or patterns, depending on the operating parameters, physical properties of the fluids, as well as geometrical variables. The flow may also be affected by pressure losses in the system, liquid holdup (as a result of density differences) e.t.c.

Russell *et al.* (1959) and Charles *et al.* (1961) (Govier *et al.*, 1972), performed series of experiments on liquid –liquid systems, in order to determine the flow patterns that were obtainable. In their work, they flowed an oil-water mixture, under varying conditions and fluid properties, through a slim tube. They drew the conclusion that the following flow patterns could possibly be obtained for a liquid-liquid system. These are: *Bubble, Slug, Mixed, Mist, Froth,* and *Stratified* (Govier *et al.,* 1972).

As a corollary to their work, they were able to develop charts and tables for determining the pressure gradient and liquid holdup for the flow of liquid-liquid systems. However, these were restrictive, in the sense that the conditions only held true for Oil-Water systems flowing through a one (1) inch diameter pipe.

In 1972, Govier *et al.* reviewed all the available material on liquid-liquid flow. They concluded that due to the complexities associated with studying liquid-liquid flow systems, no completely satisfactory general correlations for flow pattern or for holdup or pressure drop can be fully developed.

Since GTL and Crude Oil are both hydrocarbons, and as such may have very similar fluid properties, the possibility exists of blending both fluids into one homogeneous mix. This is subject to laboratory testing to determine the actual fluid properties of the resulting fluid mixture.

As part of the GTL project, tests were conducted by the Petroleum Engineering Department at the University of Alaska Fairbanks, on samples of GTL and Crude Oil (**Ramakrishnan, 2000**). From the results of the tests, it was observed that when both fluids were mixed, they blended into a single homogeneous liquid. There was no separation into distinct layers or boundaries when the mixture was left to stand.

This then allows the flexibility of treating the mixture as a single-phase homogeneous liquid, with its own unique fluid properties. In studying the commingled flow of GTL and Crude Oil through the Trans-Alaska Pipeline System, the *Bernoulli equation of pressure* for the flow of fluids in pipes is used. This equation forms the basis for any analysis in the area of fluid mechanics, and has been discussed in detail, by a great number of researchers.

2.3 OPTIMAL TRANSPORT ISSUES

The choice of an optimal transport mode is affected by a number of factors. The factors to be addressed can be summarized as follows:

i. Each transport mode requires the provision of storage and handling facilities at both ends of the pipeline.

ii. An accurate prediction of the effective slug length for batching, as well as the time taken for each batch.

iii. Interface length and time, in the case of batching, to facilitate the switching of the product train into the appropriate storage or reception facility.

iv. Pressure losses within the system.

v. Current system capabilities and ability to handle GTL, in whatever form (since TAPS was originally designed with the sole aim of handling Crude Oil).

vi. Impact on downstream refinery operations (i.e. MAPCO, Petrostar).

vii. Compare gains or cost-benefits of using TAPS for transporting GTL, as against the construction of a dedicated pipeline.

viii. Interaction of GTL with corrosion inhibitors, Drag Reducing Agents (DRA), as well as the internal mechanisms of the TAPS system.

ix. Expected hydraulic gradients for each transport mode.

x. Temperature effects on the fluid system.

Since the focus of this work is the hydraulics aspect, attention will only be placed on those relevant factors, such as slug length, pressure drop within the system, hydraulic gradient etc.

CHAPTER 3

DEVELOPMENT OF MODEL EQUATIONS

In studying the flow of Gas To Liquids and Crude Oil through the Trans Alaska Pipeline System (TAPS), in either Batch or Commingled mode, the primary concern will be on the expected pressure drop or gradient along the entire pipeline. Such pressure drop may be due to a number of reasons, such as friction, hydrostatics etc. In carrying out a proper study, the various factors that contribute to this pressure drop are examined, and the methods of accounting for them are considered. This will be achieved by presenting mathematical models or equations, which are used to obtain numerical values for these factors, and as such, allow a proper understanding of the role played by these factors in the hydraulics.

3.1 BATCH FLOW

In this transport mode, alternate batches or *slugs* of crude oil and GTL can be transported through the pipeline. This mode is also referred to as *batching* or *slugging*. A minimum slug length will be required because some mixing between the crude oil and GTL will take place at the leading and trailing edges of the slugs. The study of the expected pressure drop, that occurs during transportation in slugs or batches will focus on the minimum slug length, length of the interface (or void space) between the slugs, as well as the length of the mixing zone.

3.1.1 Assumptions

In studying the *batching* or *slugging* mode of transport, the following assumptions have been made:

i) Incompressible fluid flow, steady state and fully developed.

ii) Constant slug length.

iii) The bubble (void) between the slugs is occupied by air.

iv) The liquid film has a constant thickness.

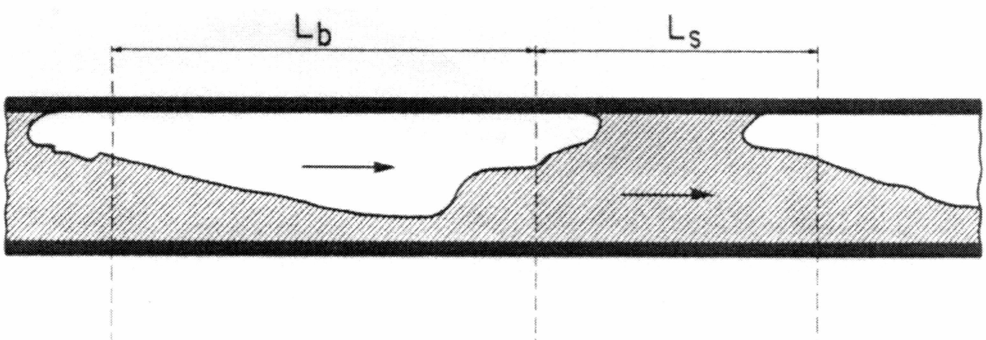
v) Flow is isothermal with constant fluid properties

vi) There is some degree of mixing between the trailing film edge and the head of the slug.

3.1.2 Governing Equations

The slug body is divided into two sections (see **Figure 3.1**), the liquid slug zone of length l_s, and the mixing zone of length, l_m. In the original work, the mixing zone was construed to consist of a liquid film, and an elongated air bubble (**Taitel, et al, 1990**). For this work, this definition has been modified, such that the mixing zone is the interface between slugs.

Figure 3.1 Schematic Representation of Slug Flow (Govier and Aziz, 1972)



The pressure drop across one slug unit is calculated from

$$\Delta P = \Delta P_f + \Delta P_a + \Delta P_h \tag{3.1.1}$$

where $\Delta P_f, \Delta P_a, \Delta P_h$ are the pressure drops due to friction, acceleration, and hydrostatic forces respectively (**Kokal, et al., 1989**; **Taitel, et al, 1990**). The pressure drops are affected by the flow regime of the fluid i.e. *laminar* (streamlined) or *turbulent*.

3.1.2.1 Pressure Drop Due To Friction

This is the pressure drop due to frictional forces within the liquid slug and the void (air pocket and liquid film). Taitel and Barnea (1990) presented Equation (3.1.2) in order to determine the pressure drop due to friction. It is a combination of the friction forces produced by the individual components of a typical slug.

$$\Delta P_f = \frac{2 f_s \rho_{mz} V_m^2 l_s}{D} + \frac{2 f_g \rho_g V_t^2 l_f}{D_g} + \frac{2 f_f \rho_l V_f^2 l_f}{D_f} \tag{3.1.2}$$

where the friction factors of the slug, f_s, air bubble, f_g, and liquid film (fluid interface zone), f_f are based on the Reynolds number of the slug, R_{es}, air bubble, R_{eg}, and the film, R_{ef}. For this work, it is assumed that the effects of the air pocket or bubble, are negligible, hence Equation (3.1.2) then becomes;

$$\Delta P_f = \frac{2 f_s \rho_l V_m^2 l_s}{D} + \frac{2 f_f \rho_{mz} V_f^2 l_m}{D_f} \tag{3.1.3}$$

The Moody friction factor is applied for laminar flow regime, and is defined as:

$$f = \frac{64}{R_e} \tag{3.1.4}$$

The Zigrang and Sylvester (1985) equation for turbulent flow, which incorporates the pipe roughness factor, ε, can be given by:

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon / D}{3.7} - \frac{5.02}{N_{R_e}}\log\left(\frac{\varepsilon / D}{3.7} + \frac{13}{N_{R_e}}\right)\right] \tag{3.1.5}$$

The Reynolds number for the slug, and film respectively, are obtained from the following expressions:

$$R_{es} = \frac{DV_m \rho_l}{\mu_l} \tag{3.1.6}$$

$$R_{emz} = \frac{D_f V_f \rho_{mz}}{\mu_{mz}} \tag{3.1.7}$$

where

$$\rho_{mz} = \rho_{l1} E_{ls} + (1 - E_{ls})\rho_{l2} \tag{3.1.8}$$

$$\mu_{mz} = \mu_{l1} E_{ls} + (1 - E_{ls})\mu_{l2} \tag{3.1.9}$$

ρ_{mz}, ρ_{l1} and ρ_{l2}, are the densities of the mixing zone and slugs respectively; μ_{mz}, μ_{l1}, and μ_{l2} are the viscosities of the mixing zone and slugs respectively; E_{ls}, is the liquid holdup in the liquid slug; E_{lf}, is the liquid holdup in the interface zone; D_f is the hydraulic diameter occupied by the interface zone.

3.1.2.2 Pressure Drop Due To Acceleration

The film velocity, V_f, just before slug pick-up, is lower than the velocity in the main body of the slug, V_s. This necessitates the acceleration of the film to match the velocity of the slug. As a result, there is a pressure drop generated by this, and it can be defined as (Kokal et al, 1989):

$$\Delta P_a = \rho_l E_{ls} (V_t - V_s)(V_s - V_f) \tag{3.1.10}$$

3.1.2.2 Hydrostatic Pressure Drop

This pressure drop can be experienced in any system because of the pipe orientation or inclination. Equation (3.1.11) was presented by Kokal *et al* (1989) and Taitel *et al* (1990) to determine the pressure drop due to pipe inclination.

$$\Delta P_h = \rho_{ms} (g \sin \beta) l_s + \rho_f (g \sin \beta) l_f \tag{3.1.11}$$

where

$$\rho_f = \rho_{l1} E_{lf} + (1 - E_{lf}) \rho_{l2} \tag{3.1.12}$$

β is the angle of inclination. Since $\sin \beta = h/L = \Delta z/L$, equation (3.1.11) can be re-written as

$$\Delta P_h = (\rho_{ms} l_s + \rho_f l_f) g \, \Delta z/L \tag{3.1.13}$$

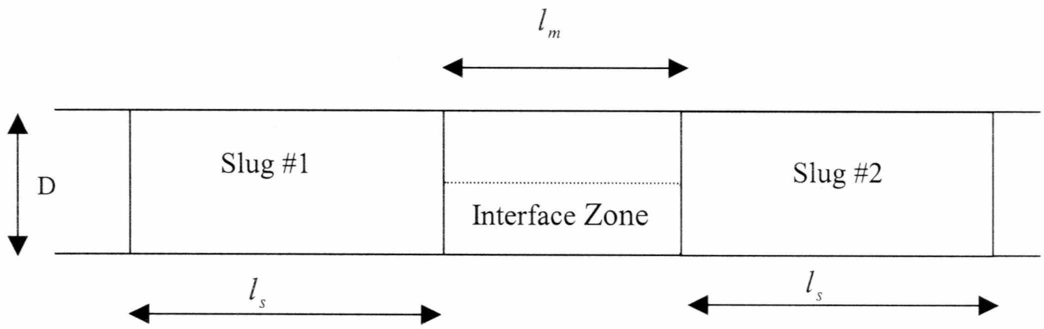
For the purposes of this work, the Equation (3.1.13) is presented as

$$\Delta P_h = (\rho_{l1} l_s + \rho_{ms} l_m) g \, \Delta z/L \tag{3.1.14}$$

The schematic arrangement of the batches or slugs, is as shown in **Figure 3.2**.

The total pressure drop across the slug can be calculated from the sum of equations (3.1.3), (3.1.10) and (3.1.14). This would require the determination of the

Figure 3.2 Schematic Representation of Batch or Slug Flow



following quantities; slug length, l_s; liquid hold-up in the slug, E_{ls}; average fluid velocity in the slug, V_s; film velocity, V_f; and length of the mixing zone, l_m.

3.1.2.3 Slug Length

This is the length of a slug. In 1986, Scott *et al.* presented a correlation for the determination of the slug length for large diameter pipes, and which is given by:

$$\ln(l_s) = -25.4144 + 28.4948(\ln(D))^{0.1} \qquad (3.1.15)$$

3.1.2.4 Average Fluid Velocity

By conducting a momentum balance over a slug unit, the average fluid velocity is given by (**Govier *et al*, 1972**; **Kokal *et al*, 1989**; **Taitel *et al*, 1990**; **Fan *et al*, 1993**; **Sharma *et al*, 1998**).

$$V_m = \frac{Q}{A} = \frac{Q_1 + Q_2}{A} = V_{s1} + V_{s2} \qquad (3.1.16)$$

where V_{s1} and V_{s2} are the superficial velocities of the slugs respectively. The average slug velocity, V_s, can be determined from equation (3.1.16) by setting it equal to the average fluid velocity.

$$V_m = V_s \tag{3.1.17}$$

3.1.2.5 Transitional Velocity

This is the slug transitional velocity. This can also be defined as the velocity of the leading edge of the slug. In 1990, Taitel and Barnea, presented a correlation, which is actually a linear combination of the interface velocity.

$$V_t = C_o V_s + V_d \tag{3.1.18}$$

where $C_o = 2$ for laminar flow, $C_o = 1.2$ for turbulent flow, and V_d is the propagation or drift velocity and is defined as (Kokal et al, 1989):

$$V_d = 0.345 \sqrt{\frac{gD(\rho_{l1} - \rho_{l2})}{\rho_{l1}}} \tag{3.1.19}$$

3.1.2.6 Liquid Slug Hold-up

When there is a difference in phase properties (density and/or viscosity), one of them, usually the less dense phase, tends to flow at a higher *in situ* average velocity than does the other. This gives rise to the existence of *slip* of one phase past the other, or *holdup* of one phase relative to the other. In 1996, Abdul-Majeed presented a correlation for the determination of the liquid holdup in the slug. It is a modification of the Lockhart-Martinelli parameter (1949). Equations (3.1.20) and (3.1.21) are for turbulent and laminar flow regimes respectively.

$$(E_{ls})_{theoretical} = \exp(-0.9304919 + 0.5285852R - 9.219634\times10^{-2}R^2 + 9.02418\times10^{-4}R^4) \tag{3.1.20}$$

$$(E_{ls})_{theoretical} = \exp(-1.099924 + 0.6788495R - 0.1232191\times10^{-2}R \\ -1.778653\times10^{-3}R^3 + 1.626819\times10^{-3}R^4) \tag{3.1.21}$$

where $R = \ln(X)$

$$X = \left[\frac{V_{s2}\rho_{l2}\mu_{l1}}{V_{s1}\rho_{l1}\mu_{l2}}\right]^m \frac{\rho_{l1}V_{s1}^2}{\rho_{l2}V_{s2}^2} \tag{3.1.22}$$

X is the Lockhart-Martinelli parameter (1949), and $m = 0.2$ for turbulent flow and $m = 1$ for laminar flow. Due to assumptions made in the development of the model, a correction was made to the value of the liquid holdup obtained from both equations:

$$(E_{ls})_{actual} = C(E_{ls})_{theoretical} \tag{3.1.23}$$

where

$$C = 0.528(V_{s2}V_{s1})^{-0.215121} \tag{3.1.24}$$

3.1.2.7 Interface Velocity

From the original data of Dukler and Hubbard (1975) model, the film velocity is given as

$$V_f = V_m\left(\frac{1}{1+\frac{0.2V_m}{\omega}}\right) \tag{3.1.25}$$

where ω is the slug frequency, and is given by equation (3.1.26) as (**Govier *et al*, 1972**)

$$\omega = 0.0226\left[\frac{V_{sl}}{gD}\left(\frac{19.75}{V_m}+V_m\right)\right]^{1.2} \tag{3.1.26}$$

3.1.2.8 Length of the Mixing Zone

This is the interface region between slugs. This interface zone is made up of mostly air pockets, and a mixture of both fluids. The magnitude of the interface zone is a function of the fluid velocity, density differences, viscosity, composition, time, pipe diameter and length. It is characterized by a rapidly varying liquid hold-up. This was originally presented in the Dukler and Hubbard model (1975) as,

$$l_m = \frac{0.15}{g}(V_m - V_f)^2 \tag{3.1.27}$$

It is observed that at large values of V_m, equation (3.1.27) largely over predicts l_m. In 1993, Andreussi et al proposed a new correlation that corrects such over predictions, and is given by:

$$l_m = k_m(1-E_{ls})D \tag{3.1.28}$$

where k_m is a factor for the length of the mixing zone and is approximately equal to 30.

3.1.2.9 Liquid Hold-up in the Mixing Zone

At steady state, the mass exchange rate between the liquid slug and the film is expressed as (**Govier *et al*, 1972**; **Dukler and Hubbard, 1975**; **Nicholson *et al*, 1978**; **Kokal *et al*, 1989**; **Taitel *et al*, 1990**):

$$\rho_l A E_{ls}(V_t - V_s) = \rho_l A E_{lf}(V_t - V_f) = \dot{m}_e \tag{3.1.29}$$

From equation (3.1.28), the film hold-up can be obtained as

$$E_{lf} = E_{ls}\frac{(V_t - V_s)}{(V_t - V_f)} \tag{3.1.30}$$

3.1.2.10 Interface Hydraulic Diameter

This is fraction of the actual pipe diameter occupied by the film (*interface*). In calculating the hydraulic diameter, the approach presented by Darby (1996) will be followed. If the height of the interface within the pipe is given as h (which can either be smaller or larger than the radius of the pipe, R), then the cross-sectional area can be obtained from equation (3.1.31a)

$$A = R^2\left[\cos^{-1}\left(1-\frac{h}{R}\right)-\left(1-\frac{h}{R}\right)\sqrt{1-\left(1-\frac{h}{R}\right)^2}\right] \tag{3.1.31a}$$

From equation (3.1.31b), the wetted perimeter can be calculated as:

$$W_p = 2R\cos^{-1}\left(1-\frac{h}{R}\right) \tag{3.1.31b}$$

As a result, the interface hydraulic diameter can then be calculated from:

$$D_f = \frac{4AE_{lf}}{W_p} \tag{3.1.31c}$$

Setting the change in elevation equal to the head loss due to friction initializes this iterative procedure,

$$\Delta z = h_f = \frac{2f_f LQ^2}{gD_f A^2} \tag{3.1.31d}$$

which is outlined as follows:

i) A value is assumed for h/R, and the parameters A, W_p and D_f are determined from equations (3.1.31a), (3.1.31b) and (3.1.31c) respectively.

ii) From equation (3.1.7) the interface Reynolds number, $N_{R_{ef}}$, is calculated.

iii) The interface frictional factor, f_f, can be computed as function of $N_{R_{ef}}$ by using equations (3.1.4) and (3.1.5).

iv) By assuming values for h/R, an iterative procedure is applied to obtain solutions to the right hand side (RHS) of equation (3.1.31d). The guessed values of h/R are continuously adjusted until a tolerance limit is reached.

3.1.2.11 Average Pressure Gradient

The average pressure gradient is determined for one complete slug unit, by dividing the total pressure drop across a slug, by the effective slug length. This is given by equation (3.1.32) as

$$\frac{\Delta P}{L} = \frac{\Delta P_f + \Delta P_a + \Delta P_h}{l_s} \tag{3.1.32}$$

3.2 COMMINGLED FLOW

In this transport mode, the GTL and Crude Oil are pre-mixed before shipment through the TAPS as a single phase. For the purpose of this analysis, it is assumed that the fluids are homogeneously mixed, and that due to the envisioned throughput, there will be no separation into distinct layers.

3.2.1 Assumptions

In studying the *commingled* mode of transport, the following assumptions will have to be made:

i) Incompressible fluid flow, steady state and fully developed

ii) Flow is isothermal with constant fluid properties.

iii) Fluid exhibits Newtonian behavior

iv) No separation into constituent fluids.

3.2.2 Governing Equations

Consider a finite element of an inviscid (frictionless) fluid, subject only to the action of gravity, (i.e. the fluid is at rest). Applying *Newton's* third law of motion to this fluid element (**Landau *et al* , 1959; Bird *et al*, 1960; Kaufmann, 1963; Streeter *et al*, 1985**)

$$F_s = dm\frac{dv}{dt} \tag{3.2.1}$$

where F_s, is the resultant of all external forces in the direction of the streamline; v, is the fluid velocity; and, dm, is the mass of the element.

The forces acting on the element are the weight and the end forces (pressure difference between the upper and lower faces), as shown in **Figure 3.3**. Thus, from equation (3.2.1),

$$\rho g \cdot ds \cdot dA \cdot \cos\theta + P \cdot dA - dA\left(P + \frac{\partial P}{\partial s} ds\right) = \rho \cdot ds \cdot dA \frac{\partial v}{\partial t} \tag{3.2.2}$$

Since θ is the angle sustained by the particle with the horizontal,

$$\cos\theta = -\frac{\partial z}{\partial s} \tag{3.2.3}$$

Equation (3.2.2) then becomes:

$$-\left(\rho g \cdot ds \cdot dA \frac{\partial z}{\partial s}\right) - \left(ds \cdot dA \cdot \frac{\partial P}{\partial s}\right) = \rho \cdot ds \cdot dA \frac{dv}{dt} \tag{3.2.4}$$

Equation (3.2.4) then simplifies to:

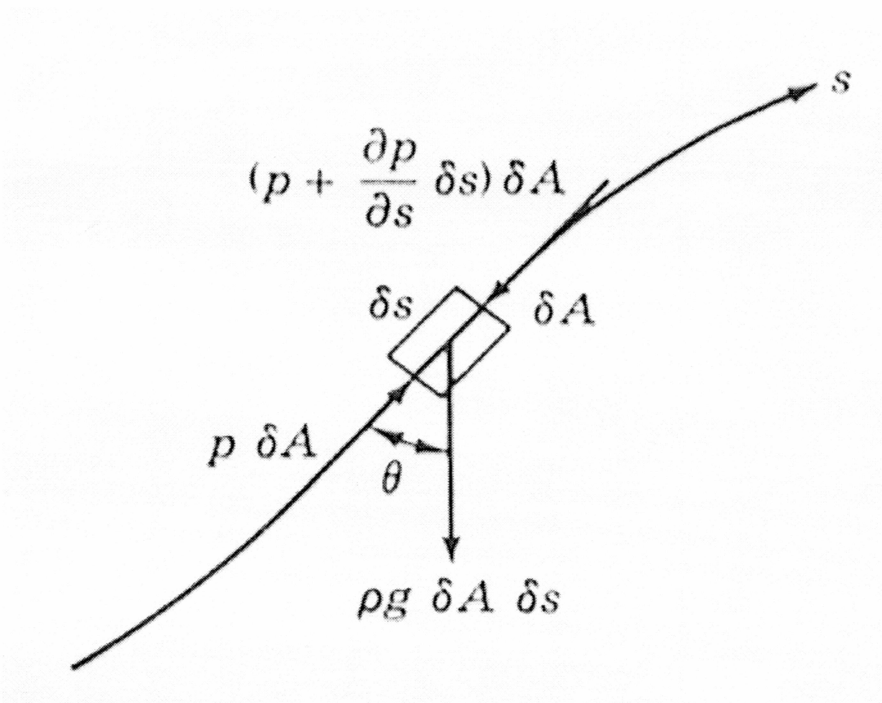
$$\frac{dv}{dt} = -g\frac{\partial z}{\partial s} - \frac{1}{\rho}\frac{\partial P}{\partial s} \tag{3.2.5}$$

In general, the fluid velocity, v, is a function of both time and location, s, along the streamline. Therefore, the total derivative for the velocity term is given as,

$$dv = \frac{\partial v}{\partial s} ds + \frac{\partial v}{\partial t} dt \tag{3.2.6}$$

Since, velocity is the rate of change of distance with time, the actual acceleration of the particle in the direction of flow becomes,

Figure 3.3 Force Balance on a Finite Element (Streeter, 1985)



$$\frac{dv}{dt} = v\frac{\partial v}{\partial s} + \frac{\partial v}{\partial t} \tag{3.2.7}$$

On the assumption of steady state flow, equation (3.2.7) reduces to,

$$\frac{dv}{dt} = v\frac{\partial v}{\partial s} \tag{3.2.8}$$

This on substitution into equation (3.2.5) and re-arranging yields

$$v\frac{\partial v}{\partial s} + g\frac{\partial z}{\partial s} + \frac{1}{\rho}\frac{\partial P}{\partial s} = 0 \tag{3.2.9}$$

Since the distance, s, is the only independent variable, the partial derivatives are replaced by total derivatives, and thus, equation (3.2.9) then becomes

$$\frac{1}{\rho}\frac{dP}{ds} + g\frac{dz}{ds} + v\frac{dv}{ds} = 0 \qquad (3.2.10)$$

Equation (3.2.10) is best known as the *Euler's equation of motion along a streamline* (Landau *et al*, 1959).

All the terms in equation (3.2.10) are derivatives with respect to distance, s. This then enables the integration along the streamline to obtain

$$\frac{v^2}{2} + \frac{P}{\rho} + gz = C_e \qquad (3.2.11)$$

where C_e is a constant. Equation (3.2.11) is more commonly known as the *Bernoulli equation of pressure in steady flow* or *the equation of energy for steady flow*.

For flow between points 1 and 2, equation (3.2.11) is written as,

$$\left(\frac{V_2^2}{2g} + \frac{P_2}{\rho_2 g} + z_2\right) - \left(\frac{V_1^2}{2g} + \frac{P_1}{\rho_1 g} + z_1\right) = C_e \qquad (3.2.12)$$

In equation (3.2.12), $V^2/2g$, and $P/(\rho g)$ are the velocity and pressure heads respectively. The last term, z, is the elevation or geometric head of the fluid above an arbitrary reference plane (**Kaufmann, 1963; Holland, 1973**).

3.2.2.1 Energy Losses

Since most natural liquids are very nearly incompressible (i.e. constant density), they are not inviscid (frictionless). Internal friction (viscosity) converts part of the flow energy into other energy forms such as sound, heat etc. and it is "lost" (**Kaufmann, 1963**). This loss is normally considered as a "head", the friction head, h_f, and is given by the *Darcy-Weisbach* equation (**Smith *et al*, 1960**) as:

$$h_f = 4f\frac{LV^2}{2gD} \tag{3.2.13}$$

Therefore, equation (3.2.12) is re-written as,

$$\left(\frac{V_1^2}{2g}+\frac{P_1}{\rho\, g}+z_1\right)=\left(\frac{V_2^2}{2g}+\frac{P_2}{\rho g}+z_2\right)+h_f \tag{3.2.14}$$

For steady incompressible flow through a pipe, between points 1 and 2, with a pump at one end, equation (3.2.14) can be re-written as,

$$\left(\frac{V_2^2}{2g}+\frac{P_2}{\rho g}+z_2\right)-\left(\frac{V_1^2}{2g}+\frac{P_1}{\rho g}+z_1\right)=\Delta h_p - h_f \tag{3.2.15}$$

where Δh_p, is the head imparted to the fluid by the pump (**Holland, 1973**).

This then implies that the total pressure drop across the streamline is given as

$$\frac{P_1-P_2}{\rho g}=\frac{\left(V_1^2-V_2^2\right)}{2g}+\left(z_2-z_1\right)+\left(h_f-\Delta h_p\right) \tag{3.2.16}$$

or simply

$$\Delta P = \rho g\left[\left(\frac{V_2^2 - V_1^2}{2g}\right) + \left(z_2 - z_1\right) + \left(h_f - \Delta h_p\right)\right] \tag{3.2.17}$$

Equation (3.2.17) will form the basis for the study of the commingled flow of GTL and Crude Oil through TAPS.

CHAPTER 4

APPLICATION OF MODEL EQUATIONS

In choosing the appropriate mode for transporting GTL through TAPS, i.e. either batch or commingled flow, the derived model equations will have to be applied to estimate the expected pressure drop for each mode. Based on the results obtained from the computations, a reasonable choice can then be made.

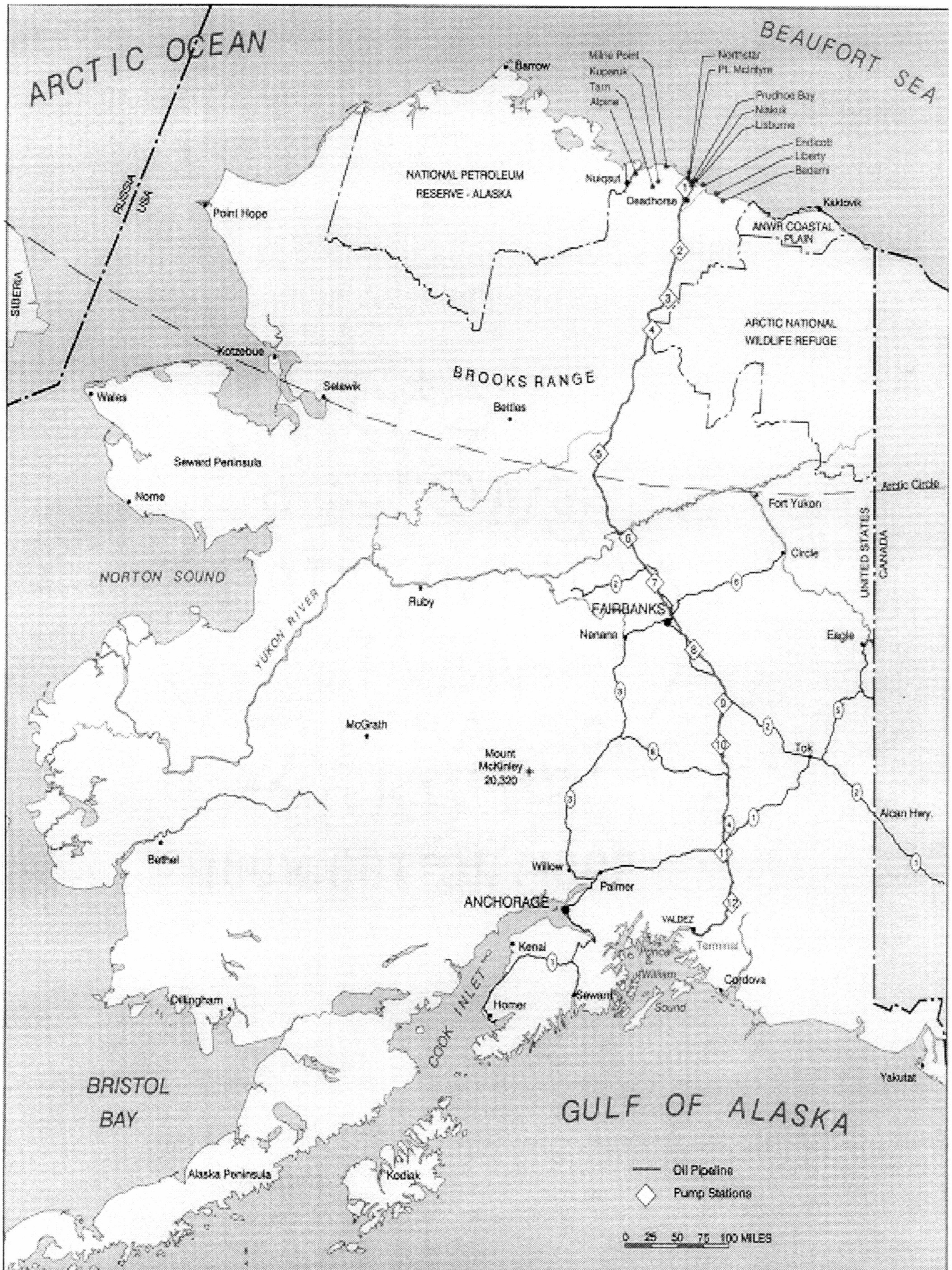
4.1 CALCULATION ALGORITHM

The Trans-Alaska Pipeline System (TAPS) is an 800 miles and 48" diameter pipeline, as shown in **Figure 4.1**. For computational purposes, it has been divided into six (6) major pipe sections. These sections are as follows:

i. Pump Station #1 to Pump Station #3 (Length, L = 104.27 mi.; Change in elevation, Δz = +1344.3 ft.)
ii. Pump Station #3 to Pump Station #4 (L = 39.79 mi.; Δz = +1380 ft.)
iii. Pump Station #4 to Pump Station #7 (L = 270.02 mi.; Δz = -1859.1 ft.)
iv. Pump Station #7 to Pump Station #9 (L = 134.66 mi.; Δz = + 604.3 ft.)
v. Pump Station #9 to Pump Station #12 (L = 186.36 mi.; Δz = +312.6 ft.)
vi. Pump Station #12 to Valdez Terminal (L = 65.1 mi.; Δz = -1655.4 ft.)

The successful application of the model equations requires a prior knowledge of fluid properties, such as density and viscosity. Also important, is the knowledge of the pipe parameters (diameter, length, geometry), as well as current operating conditions (flow rate, pump information, pipe specifications). The systematic procedures necessary for the determination of the total pressure drop, as well as the average pressure gradient, are outlined in the following sections.

Figure 4.1 Map Showing the Path of TAPS from PS1 to Valdez Terminal



4.1.1 Batch Flow

For this transport mode, the focus will also be on the determination of the average slug length, length of the mixing zone, and liquid holdup in the slug.

The sequential steps, which are carried out for each pipe section, are outlined as follows:

i. From equation (3.1.16), the mixture velocity, V_m, is calculated as a function of the fluid flow rates.

ii. The transitional velocity, V_t, is calculated by combining equations (3.1.18) and (3.1.19).

iii. The determination of the liquid holdup in the slug is a four (4) step process, which can be listed as;

   a) Determine the *Lockhart-Martinelli* parameter, X, from equation (3.1.22)

   b) From equation (3.1.24), the correction factor, C, is obtained.

   c) The theoretical liquid holdup is obtained from either equations (3.1.20) or (3.1.21).

   d) Using the value obtained for C from (b) above, the true liquid holdup is calculated using equation (3.1.23).

iv. The length of the slug, l_s, is obtained by using equation (3.1.15).

v. From equation (3.1.28), the length of the mixing zone, l_m, is calculated.

vi. The interface velocity, V_f, is obtained from equation (3.1.25), as a function of V_m, and the slug frequency, ω, obtained from equation (3.1.26).

vii. From equations (3.1.31a-d), a value for the effective diameter of the interface or film, is obtained.

viii. Using equations (3.1.6) and (3.1.7), the *Reynolds* number, N_{R_e}, for the slug, and film, are calculated as functions of densities, velocities, diameters, and viscosities.

ix. Depending on the flow regime, the appropriate friction factor, f, is calculated as a function of the Reynolds' number, using either equation (3.1.4) or (3.1.5).

x. The pressure drop due to friction, ΔP_f, is calculated from equation (3.1.2).

xi. The pressure drop due to acceleration, ΔP_a, is calculated from equation (3.1.10).

xii. The hydrostatic pressure drop, ΔP_h, is calculated from equation (3.1.14).

xiii. The average pressure gradient, $\Delta P/L$, is calculated from equation (3.1.32).

The total pressure drop is the sum of the individual pressure drops across each pipe section. The flowchart for these procedures is as shown in **Figure 4.2**.

4.1.2 Commingled Flow

In this mode, since there is prior mixing of both GTL and Crude Oil before transport, the analysis will be conducted similar to that of a single-phase fluid. The focus will also be on the expected pressure drop across each pipe segment.

The sequential steps, which are carried out for each pipe section, are outlined as follows:

i. The initial fluid velocity, V_1, is calculated as a function of fluid flow rate, Q, and pipe cross-sectional area, A (similar to equation (3.1.15)).

ii. From equation (3.1.5), the Reynolds' number, N_{R_e}, is calculated, in order to determine the appropriate flow regime (for laminar flow, N_{R_e} $\leq$ 2000, and for turbulent flow, N_{R_e} > 2000).

iii. Depending on the flow regime, the appropriate friction factor, f, is calculated as a function of the Reynolds' number, using either equation (3.1.3) or (3.1.4).

iv. From equation (3.2.13), the head loss due to friction, h_f, is calculated as a function of the friction factor.

v. Based on the flow rates and number of pumps in service, the head imparted to the fluid by the pumps, Δh_p, can be determined (Note: Since this analysis is based on already existing equipment, this data would have to be obtained from the pump design and specification sheet).

vi. The pressure drop, ΔP, is determined from equation (3.2.17) (Note: Steady state flow, therefore, $V_1 = V_2 = V$).

The total pressure drop is the sum of the individual pressure drops across each pipe section. The flowchart for these procedures is as shown in **Figure 4.3.**

In general, the total pressure drop, ΔP_t, is calculated as:

$$\Delta P_t = \Delta P_1 + \Delta P_2 + \Delta P_3 + \Delta P_4 + \Delta P_5 + \Delta P_6 \tag{4.1}$$

4.2 EXAMPLE CALCULATION

The calculation path for each mode has been transcribed into computer code for use in the Microsoft Excel (®) Spreadsheet program. The code, which is written in the Visual Basic environment, is as shown in **Appendix A**. In this section, a sample step-by step calculation for each mode will be performed, for a given set of input data.

4.2.1 Batch Flow

The following assumptions will have to be made at the start of the calculation;

i. Equal and constant flow rates for both slugs.

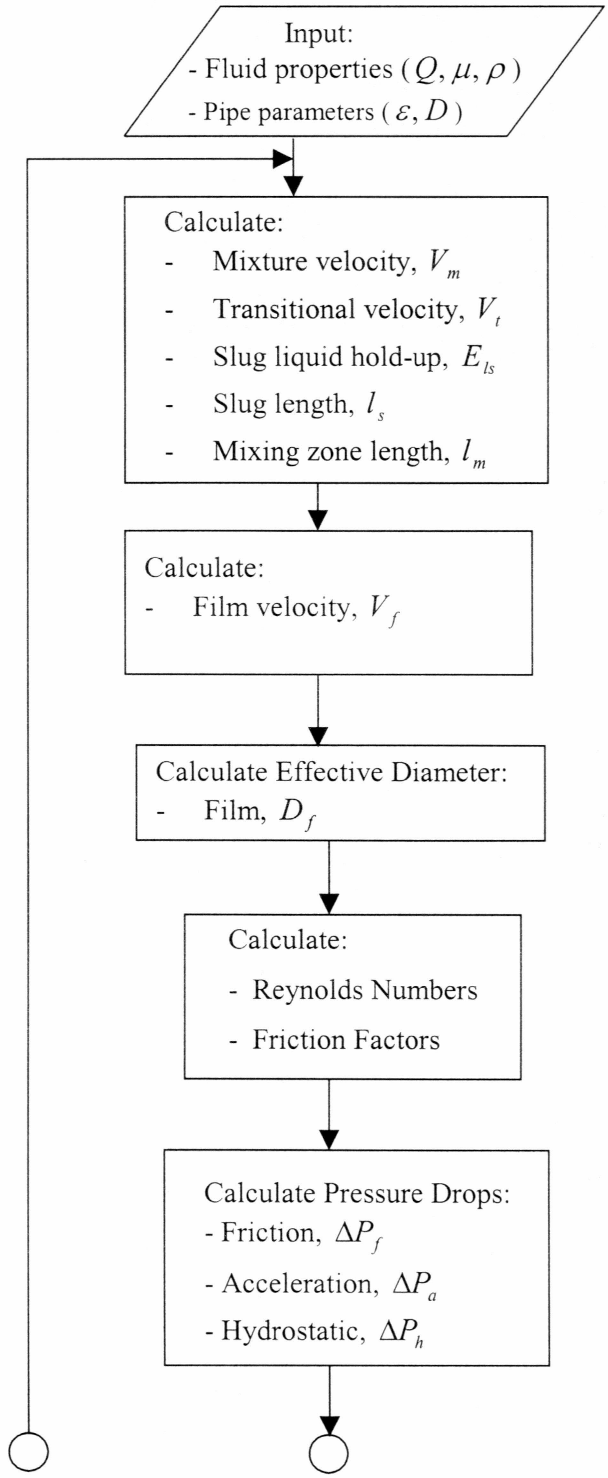
ii. Constant slug length.

iii. Constant interface zone length.

iv. Flow is isothermal, with constant fluid properties.

v. Each fluid exhibits Newtonian behavior.

Figure 4.2 Calculation Flowchart for Batch Flow



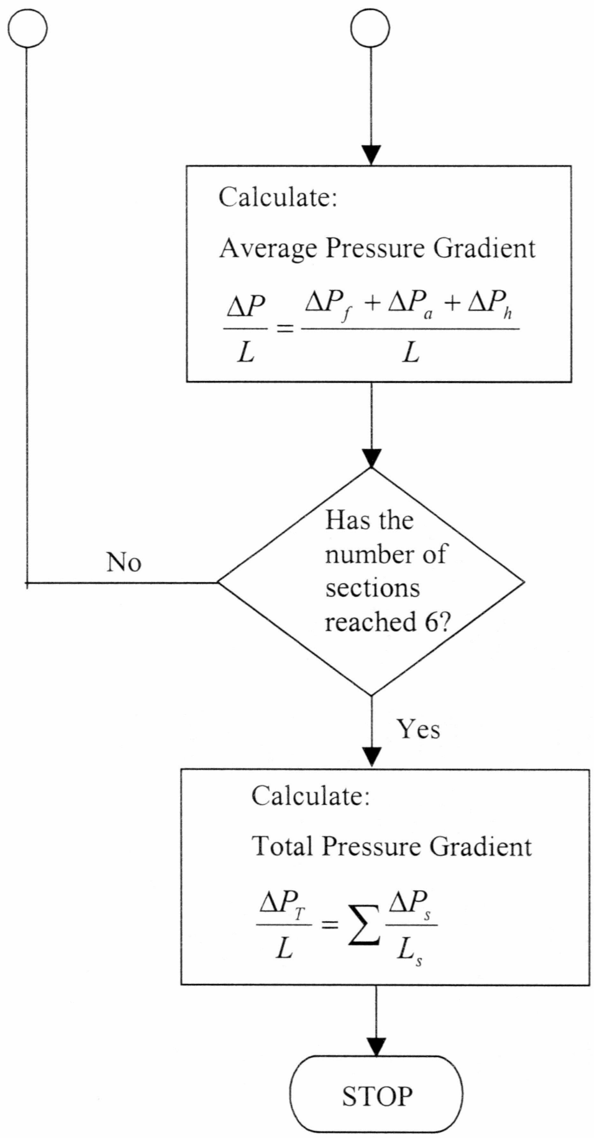
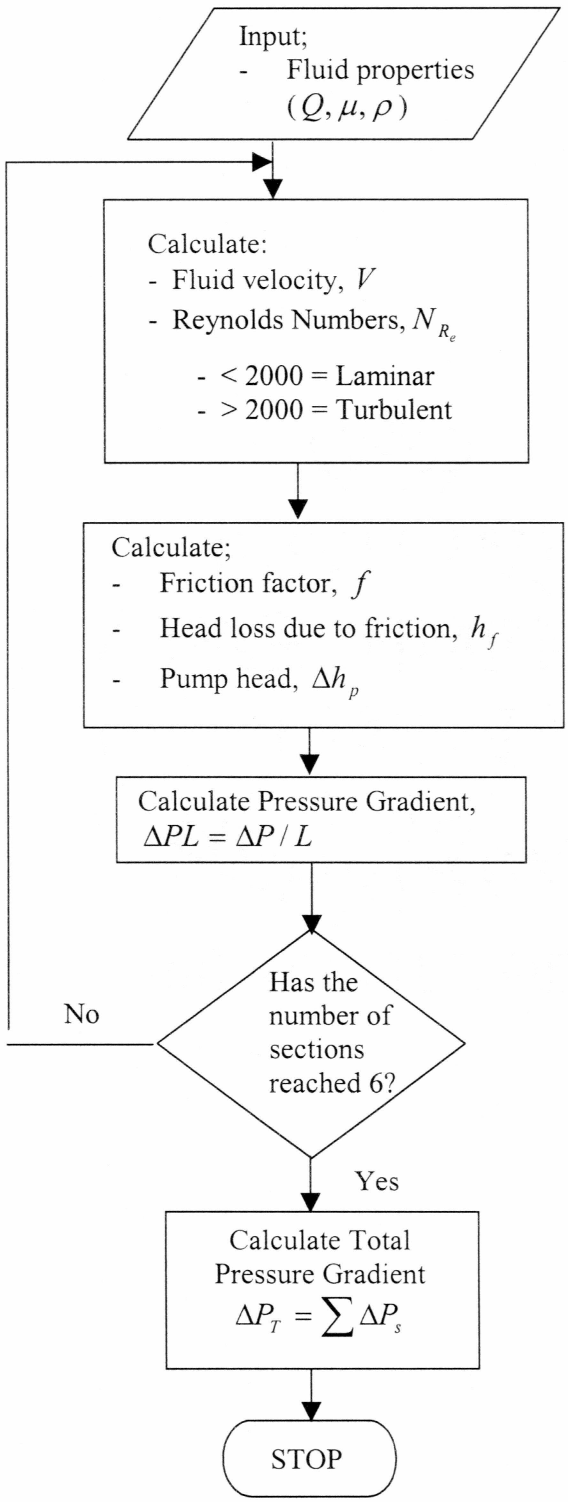

Calculate:
Average Pressure Gradient
$\frac{\Delta P}{L} = \frac{\Delta P_f + \Delta P_a + \Delta P_h}{L}$
Has the number of sections reached 6?
No
Yes
Calculate:
Total Pressure Gradient
$\frac{\Delta P_T}{L} = \sum \frac{\Delta P_s}{L_s}$
STOP

Figure 4.3 Calculation Flowchart for Commingled Flow



vi. Hydraulic diameter for the interface zone is assumed a fraction of the actual pipe diameter (maximum of 0.5 x Pipe diameter).

vii. Constant pipe roughness.

viii. All other losses along the line are neglected.

ix. All computations are in field units.

Example: For a daily throughput of 1.1MMBPD of both Crude Oil and GTL, what is the expected pressure gradient for each pipe segment?

Necessary Data:

Inlet Temperature = 90^{O}F

Crude Oil: Specific Gravity = 0.8614, Viscosity = 6.2 cP

GTL: Specific Gravity = 0.73, Viscosity = 1.0 cP

(Note: The fluid properties can be obtained from **Figures 4.4** and **4.5**)

Pipe Diameter = 48 in. = 4 ft

Pipe roughness = 0.00001 ft

Interface Diameter ratio = 0.3

Solution:

General Data

- Convert the given flow rates from BPD to ft^3/sec:

$$Q_1 = Q_2 = \frac{1.1*10^6*42*0.1337}{24*60*60} = 71.492\ ft^3/s$$

- From equation 3.1.16, the superficial velocities are calculated as;

$$V_{s1} = V_{s2} = \frac{Q}{A} = \frac{4*Q}{\pi*D^2} = \frac{4*71.492}{3.142*4^2} = 5.688\ ft/s$$

thus, the slug velocity is given as;

$$V_m = V_{s1} + V_{s2} = 11.376\ ft/s$$

- From equations (3.1.18 – 19), the transitional velocity is given as;

$$V_t = 15.183\ ft/s$$

Figure 4.4 Mixture Viscosity .vs. Temperature at Atmospheric Pressure (Ramakrishnan, 2000)

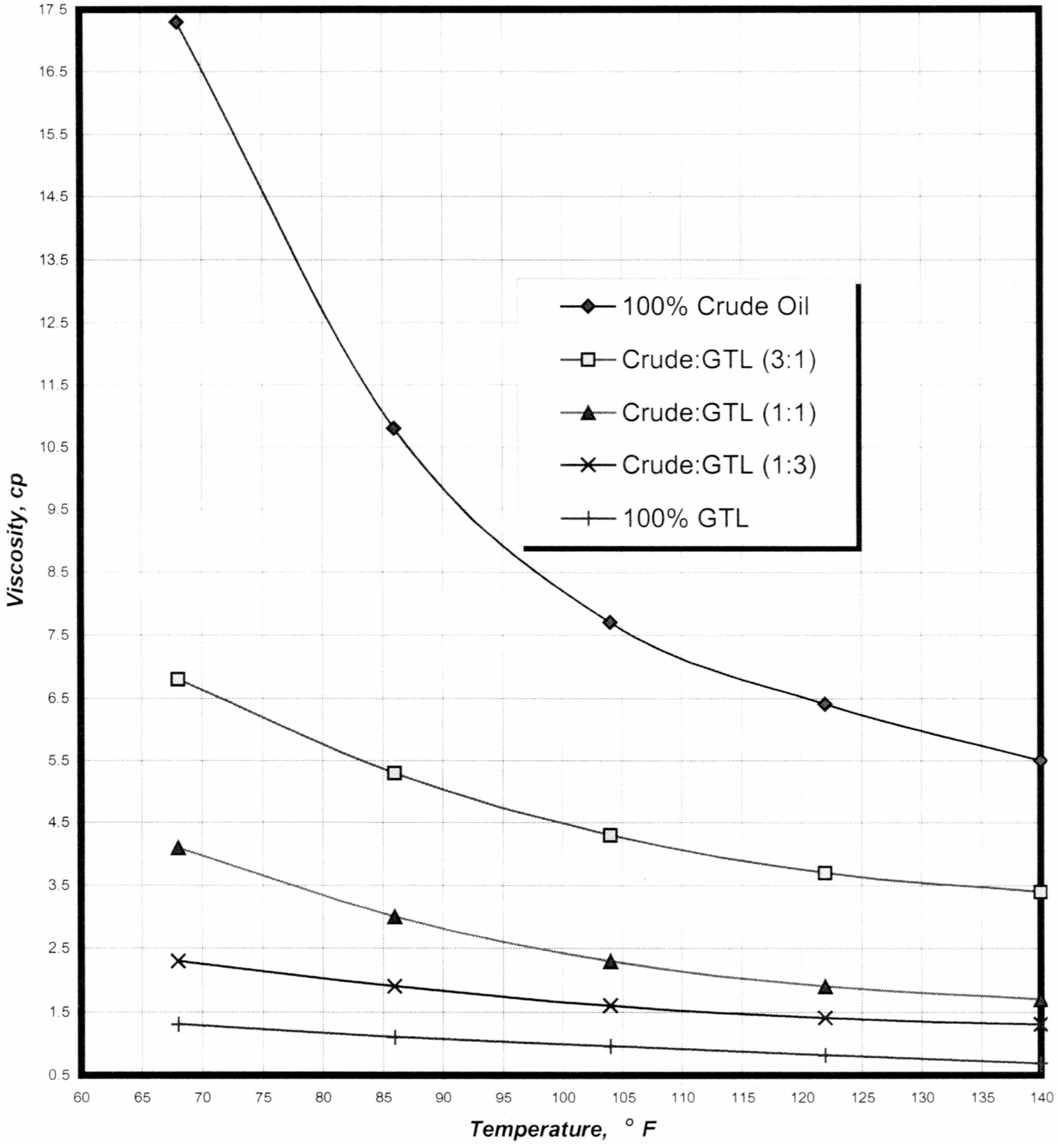
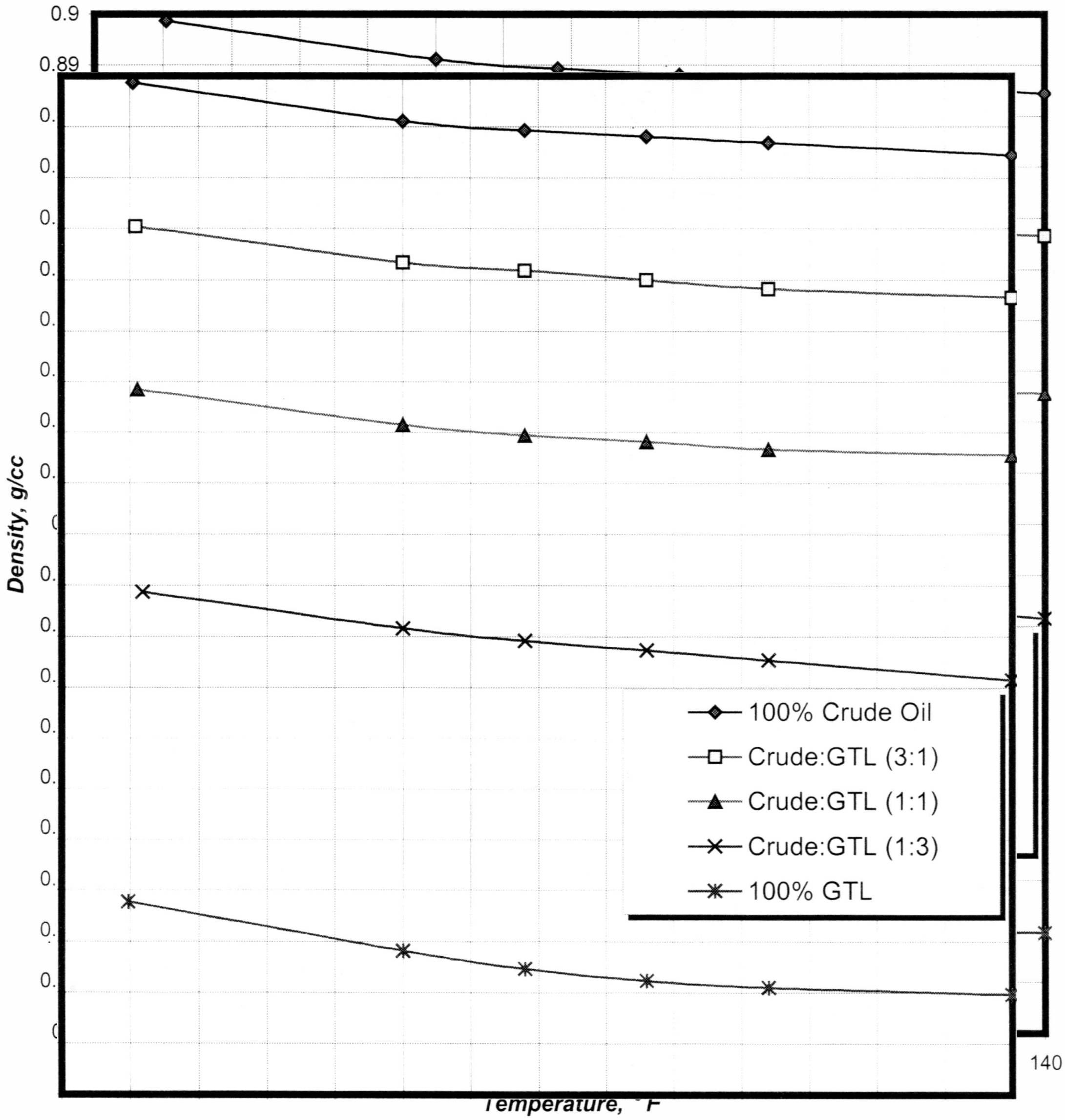


Figure 4.5 Mixture Density .vs. Temperature at Atmospheric Pressure (Ramakrishnan, 2000)



Slug Properties

- From Equation 3.1.15, the slug length is calculated as;

  $$l_s = 1353.67\,ft$$

- The liquid holdup in the slug is computed from equations 3.1.20 - 3.1.24 as;

  $$E_{ls} = 0.125$$

Interface Zone Properties

- From Equation 3.1.28, the interface zone length is calculated as;

  $$l_m = 104.964\,ft$$

- The liquid holdup in the interface zone is computed from equation 3.1.30 as;

  $$E_{lm} = 3.374 * 10^{-2}$$

- The interface fluid velocity is computed from equations 3.1.25 and 3.1.26 as;

  $$V_f = 1.051\,ft/s$$

Pipe Segment #1 (Pump Station #1 – Pump Station #3)

- Distance = 104.27 miles = 550,545.6 ft
- Change in elevation = 1,344.3 ft

  (The length and change in elevation for each pipe segment, is obtained from Alyeska Pipeline Service Company)
- For the interface zone;
  - From equations 3.1.8 and 3.1.9, the fluid properties of the zone are computed as;

    $$\rho_{mz} = 6.125 \text{ lb/gal}$$

    $$\mu_{mz} = 1.175 \text{ cP}$$

  - Hence, the Reynolds number can be computed from equation 3.1.7 as;

    $$R_{emz} = \frac{928\rho_{mz}V_f D_f}{\mu_{zs}} = \frac{928*1.051*6.125*0.3*48}{1.175} = 73165$$

- Since $N_{R_e} > 2000$, this indicates turbulent flow, and the friction factor is computed from equation 3.1.5, as;

$$f_m = 4.538 \text{ x } 10^{-3}$$

- For the slug;
  - The Reynolds number is computed as;

$$R_{es} = \frac{928\rho_{ls}V_m D}{\mu_{ls}} = \frac{928*11.376*7.184*48}{6.2} = 587{,}284$$

  - Since $N_{R_e} > 2000$, this indicates turbulent flow, and the friction factor is computed from equation 3.1.5, as;

$$f_s = 2.928 \text{ x } 10^{-3}$$

- Pressure drop due to friction, from equation 3.1.3;
  - For the slug: $\Delta P_{fs} = 345.018$ psi
  - For the interface zone: $\Delta P_{fm} = 0.999$ psi
  - Total pressure drop due to friction:

$$\Delta P_f = \Delta P_{fs} + \Delta P_{fm} = 346.017 \text{ psi}$$

- Pressure drop due to acceleration, from equation 3.1.10;

$$\Delta P_a = 6.622 \text{ psi}$$

- Pressure drop due to hydrostatics, from equation 3.1.14;

$$\Delta P_h = \frac{0.17068*(7.184*1353.67+6.125*104.964)*1{,}344.3}{550{,}545.6}$$

$$= 4.321 \text{ psi}$$

- Total pressure drop across slug, from equation 3.1.1;

$$\Delta P_T = \Delta P_f + \Delta P_a + \Delta P_h$$

$$= 356.993 \text{ psi}$$

- Average pressure gradient across a complete slug unit, from equation 3.1.32;

$$\Delta P / L = \Delta P_T / l_s = 356.993/1353.67 = 0.264 \text{ psi/ft}$$

In view of earlier assumptions made in the model development, for the other pipe segments the difference will be in the computed values of the hydrostatic pressure drop, and ultimately, the total pressure drop. This occurs because of the differences in segment length and elevation.

Pipe Segment #2 (Pump Station #3 – Pump Station #4)

- Distance = 39.79 miles = 210,091.2 ft
- Change in elevation = 1,380 ft
- Pressure drop due to hydrostatics, from equation 3.1.14;

$$\Delta P_h = \frac{0.17068 * (7.184 * 1353.67 + 6.125 * 104.964) * 1{,}380}{210{,}091.2} = 11.624 \text{ psi}$$

- Total pressure drop across slug, from equation 3.1.1;

$$\Delta P_T = 364.264 \text{ psi}$$

- Average pressure gradient across a complete slug unit, from equation 3.1.32;

$$\Delta P / L = 0.269 \text{ psi/ft}$$

Pipe Segment #3 (Pump Station #4 – Pump Station #7)

- Distance = 270.02 miles = 1,425,705.6 ft
- Change in elevation = -1,859 ft
- Pressure drop due to hydrostatics, from equation 3.1.14;

$$\Delta P_h = \frac{0.17068 * (7.184 * 1353.67 + 6.125 * 104.964) * -1{,}859}{1{,}425{,}705.6} = -2.308 \text{ psi}$$

  (the value obtained here, is as a result of the drop in elevation between Pump Station #4 and Pump Station #7)
- Total pressure drop across slug, from equation 3.1.1;

$$\Delta P_T = 350.332 \text{ psi}$$

- Average pressure gradient across a complete slug unit, from equation 3.1.32;

$$\Delta P / L = 0.259 \text{ psi/ft}$$

Pipe Segment #4 (Pump Station #7 – Pump Station #9)

- Distance = 134.66 miles = 711,004.8 ft
- Change in elevation = 604.3 ft
- Pressure drop due to hydrostatics, from equation 3.1.14;

$$\Delta P_h = \frac{0.17068*(7.184*1353.67+6.125*104.964)*604.3}{711,004.8} = 1.504 \text{ psi}$$

- Total pressure drop across slug, from equation 3.1.1;

$$\Delta P_T = 354.144 \text{ psi}$$

- Average pressure gradient across a complete slug unit, from equation 3.1.32;

$$\Delta P / L = 0.262 \text{ psi/ft}$$

Pipe Segment #5 (Pump Station #9 – Pump Station #12)

- Distance = 186.36 miles = 983,980.8 ft
- Change in elevation = 312.6 ft
- Pressure drop due to hydrostatics, from equation 3.1.14;

$$\Delta P_h = \frac{0.17068*(7.184*1353.67+6.125*104.964)*312.6}{983,980.8} = 0.562 \text{ psi}$$

- Total pressure drop across slug, from equation 3.1.1;

$$\Delta P_T = 353.202 \text{ psi}$$

- Average pressure gradient across a complete slug unit, from equation 3.1.32;

$$\Delta P / L = 0.261 \text{ psi/ft}$$

Pipe Segment #6 (Pump Station #12 – Valdez Terminal)

- Distance = 65.1 miles = 343,728 ft
- Change in elevation = -1655.4 ft
- Pressure drop due to hydrostatics, from equation 3.1.14;

$$\Delta P_h = \frac{0.17068*(7.184*1353.67+6.125*104.964)*-1,655.4}{343,728} = -8.522 \text{ psi}$$

(the value obtained here, is as a result of the drop in elevation between Pump Station #12 and Valdez Marine Terminal)

- Total pressure drop across slug, from equation 3.1.1;

$$\Delta P_T \;\; = 344.118 \text{ psi}$$

- Average pressure gradient across a complete slug unit, from equation 3.1.32;

$$\Delta P/L \;\; = 0.254 \text{ psi/ft}$$

4.2.2 Commingled Flow

The following assumptions will have to be made at the start of the calculation;

i. Single phase fluid
ii. Constant flow rate
iii. Incompressible fluid flow, steady state and fully developed
iv. Flow is isothermal with constant fluid properties.
v. Fluid exhibits Newtonian behavior
vi. No separation into constituent fluids.
vii. A numeric value is assigned to account for the pressure loss due to fittings.
viii. The head provided by the pumps is computed from a pump specification spreadsheet, provided by APSC.

Example: For a daily throughput of 1.1 MMBPD of commingled fluid (i.e. GTL and Crude Oil, for this case, there's a 1:1 ratio). What is the expected pressure gradient for each pipe segment?

Necessary Data:

Inlet Temperature = 90^{O}F

Fluid: Specific Gravity = 0.833, Viscosity = 2.8 cP

(Note: The fluid properties can be obtained from **Figure 4.4** and **4.5**)

Pipe Diameter = 48 in. = 4 ft

Pipe Roughness = 0.00001 ft

Solution:

General Data

- Convert the given flow rates from BPD to ft^3/sec:

$$Q = \frac{1.1*10^6 * 42 * 0.1337}{24 * 60 * 60} = 71.492\, ft^3/s$$

- Similar to equation 3.1.16, the fluid velocity is calculated as;

$$V = \frac{Q}{A} = \frac{4*Q}{\pi * D^2} = \frac{4*71.492}{3.142*4^2} = 5.688\, ft/s$$

- Hence, the Reynolds number can be computed using an equation similar to equation 3.1.7 ;

$$R_e = \frac{928\rho_l VD}{\mu} = \frac{928*6.947*5.688*48}{2.8} = 628{,}620$$

- Since $N_{R_e} > 2000$, this indicates turbulent flow, and the friction factor is computed from equation 3.1.5, as;

$$f_s = 2.892 \text{ x } 10^{-3}$$

Pipe Segment #1 (Pump Station #1 – Pump Station #3)

- Distance = 104.27 miles = 550,545.6 ft
- Change in elevation = 1,344.3 ft

  (The length and change in elevation for each pipe segment, is obtained from Alyeska Pipeline Service Company data)
- Head loss due to friction, from equation 3.2.13;

$$h_f = \frac{4*f*L*V^2}{2gD} = \frac{4*2.892*10^{-3}*550{,}545.6*5.688^2}{2*32.2*4} = 799.913 \text{ ft}$$

- Head supplied by pumps, (from APSC pump data specification spreadsheet)

$$h_P = 5478.824 \text{ ft}$$

- Pressure losses through fittings, ΔP_{fit} = 60.5 psi (assumed value)
- From equation 3.2.17, the total pressure drop is given as

$$\Delta P = \frac{\rho g(h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = \frac{51.955 * 32.2 * (h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = 38{,}801.095 \text{ psi}$$

- The pressure gradient can then be calculated as

  $\Delta P/L$ = 7.048 x 10^{-2} psi/ft

Pipe Segment #2 (Pump Station #3 – Pump Station #4)

- Distance = 39.79 miles = 210,091.2 ft
- Change in elevation = 1,380 ft
- Head loss due to friction, from equation 3.2.13;

$$h_f = \frac{4 * f * L * V^2}{2gD} = \frac{4 * 2.892 * 10^{-3} * 210{,}091.2 * 5.688^2}{2 * 32.2 * 4} = 215.871 \text{ ft}$$

- Head supplied by pumps, (from APSC pump data specification spreadsheet)

  $h_p = 5478.824$ ft

- Pressure losses through fittings, ΔP_{fit} = 52 psi (assumed value)
- From equation 3.2.17, the total pressure drop is given as

$$\Delta P = \frac{\rho g(h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = \frac{51.955 * 32.2 * (h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = 45{,}169.608 \text{ psi}$$

- The pressure gradient can then be calculated as

  $\Delta P/L$ = 2.15 x 10^{-1} psi/ft

Pipe Segment #3 (Pump Station #4 – Pump Station #7)

- Distance = 270.02 miles = 1,425,705.6 ft
- Change in elevation = -1,859 ft
- Head loss due to friction, from equation 3.2.13;

$$h_f = \frac{4 * f * L * V^2}{2gD} = \frac{4 * 2.892 * 10^{-3} * 1{,}425{,}705.6 * 5.688^2}{2 * 32.2 * 4} = 1464.926 \text{ ft}$$

- Head supplied by pumps, (from APSC pump data specification spreadsheet)

  $h_p = 5478.824$ ft

- Pressure losses through fittings, $\Delta P_{fit} = 61$ psi (assumed value)

- From equation 3.2.17, the total pressure drop is given as

$$\Delta P = \frac{\rho g(h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = \frac{51.955 * 32.2 * (h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = 68{,}291.27 \text{ psi}$$

- The pressure gradient can then be calculated as

  $\Delta P/L = 4.79 \times 10^{-2}$ psi/ft

Pipe Segment #4 (Pump Station #7 – Pump Station #9)

- Distance = 134.66 miles = 711,004.8 ft
- Change in elevation = 604.3 ft
- Head loss due to friction, from equation 3.2.13;

$$h_f = \frac{4 * f * L * V^2}{2gD} = \frac{4 * 2.892 * 10^{-3} * 711{,}004.8 * 5.688^2}{2 * 32.2 * 4} = 730.564 \text{ ft}$$

- Head supplied by pumps, (from APSC pump data specification spreadsheet)

  $h_p = 2746.7093$ ft

- Pressure losses through fittings, $\Delta P_{fit} = 59$ psi (assumed value)

- From equation 3.2.17, the total pressure drop is given as

$$\Delta P = \frac{\rho g(h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = \frac{51.955 * 32.2 * (h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = 16{,}388.661 \text{ psi}$$

- The pressure gradient can then be calculated as

  $\Delta P/L = 2.315 \times 10^{-2}$ psi/ft

Pipe Segment #5 (Pump Station #9 – Pump Station #12)

- Distance = 186.36 miles = 983,980.8 ft
- Change in elevation = 312.6 ft
- Head loss due to friction, from equation 3.2.13;

$$h_f = \frac{4*f*L*V^2}{2gD} = \frac{4*2.892*10^{-3}*983{,}980.8*5.688^2}{2*32.2*4} = 1011.049 \text{ ft}$$

- Head supplied by pumps, (from APSC pump data specification spreadsheet)

$$h_p = 5262.606 \text{ ft}$$

- Pressure losses through fittings, $\Delta P_{fit} = 57.5$ psi (assumed value)
- From equation 3.2.17, the total pressure drop is given as

$$\Delta P = \frac{\rho g(h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = \frac{51.955*32.2*(h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = 45{,}819.066 \text{ psi}$$

- The pressure gradient can then be calculated as

$$\Delta P/L = 4.657 \times 10^{-2} \text{ psi/ft}$$

Pipe Segment #6 (Pump Station #12 – Valdez Marine Terminal)

- Distance = 65.1 miles = 343,728 ft
- Change in elevation = -1655.4 ft
- Head loss due to friction, from equation 3.2.13;

$$h_f = \frac{4*f*L*V^2}{2gD} = \frac{4*2.892*10^{-3}*983{,}980.8*5.688^2}{2*32.2*4} = 353.184 \text{ ft}$$

- Head supplied by pumps, (from APSC pump data specification spreadsheet)

$$h_p = 765.679 \text{ ft}$$

- Pressure losses through fittings, $\Delta P_{fit} = 51$ psi (assumed value)
- From equation 3.2.17, the total pressure drop is given as

$$\Delta P = \frac{\rho g(h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = \frac{51.955*32.2*(h_p - (\Delta z + h_f))}{144} + \Delta P_{fit} = 24{,}075.397 \text{ psi}$$

- The pressure gradient can then be calculated as

$$\Delta P/L = 7.004 \text{ x } 10^{-2} \text{ psi/ft}$$

The sample calculations were also carried out for different blending ratios of GTL and Crude Oil. The ratios considered were;

i. 100% Crude Oil

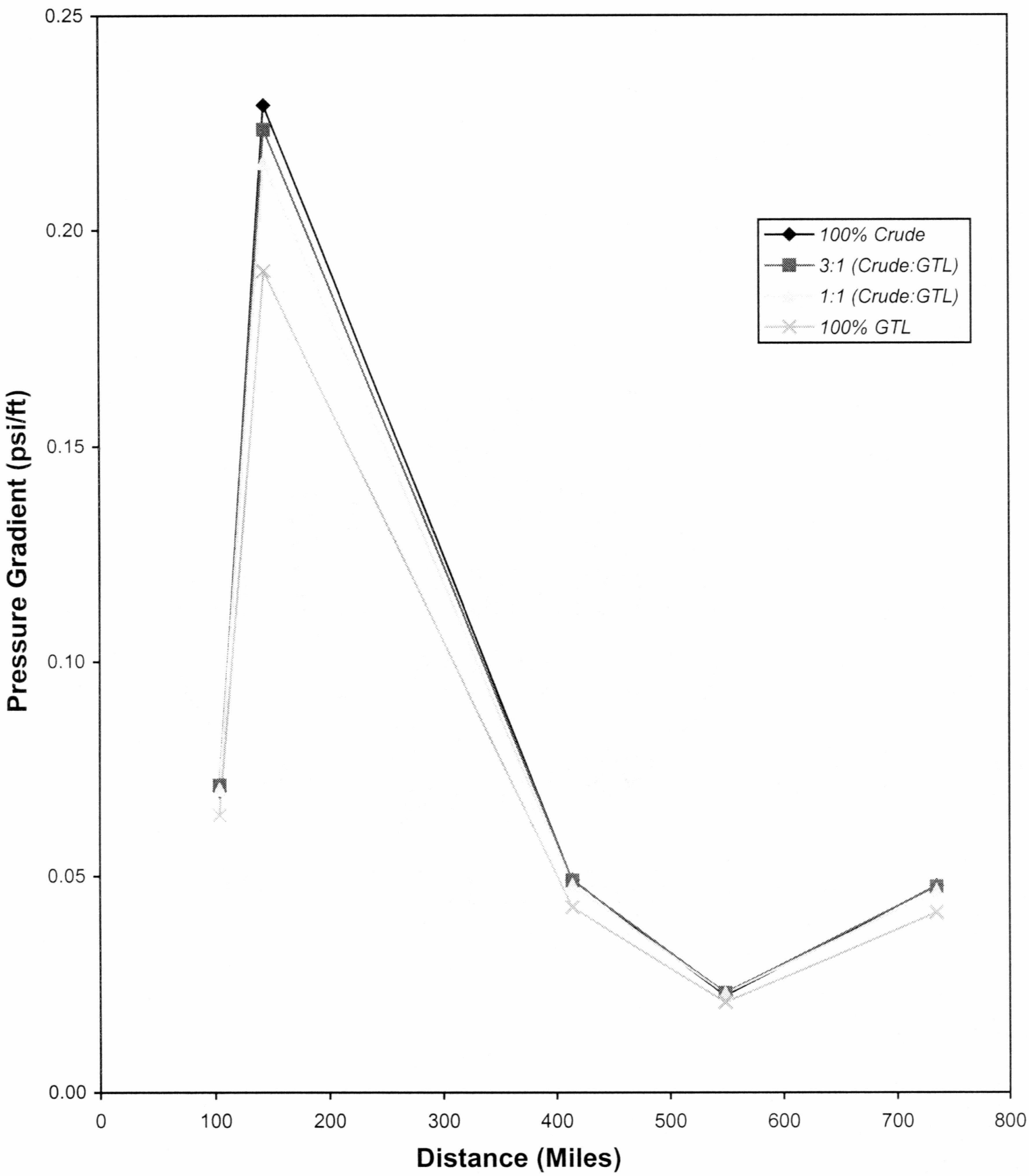
ii. 75% Crude Oil + 25% GTL (3:1 ratio)

iii. 50% Crude Oil + 50% GTL (1:1 ratio)

iv. 100% GTL

The pressure gradients obtained from these computations are as shown in **Figure 4.6**.

Figure 4.6 Pressure Gradient Plot for Commingled Flow



CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The following conclusions are made, based on the results presented in this study:

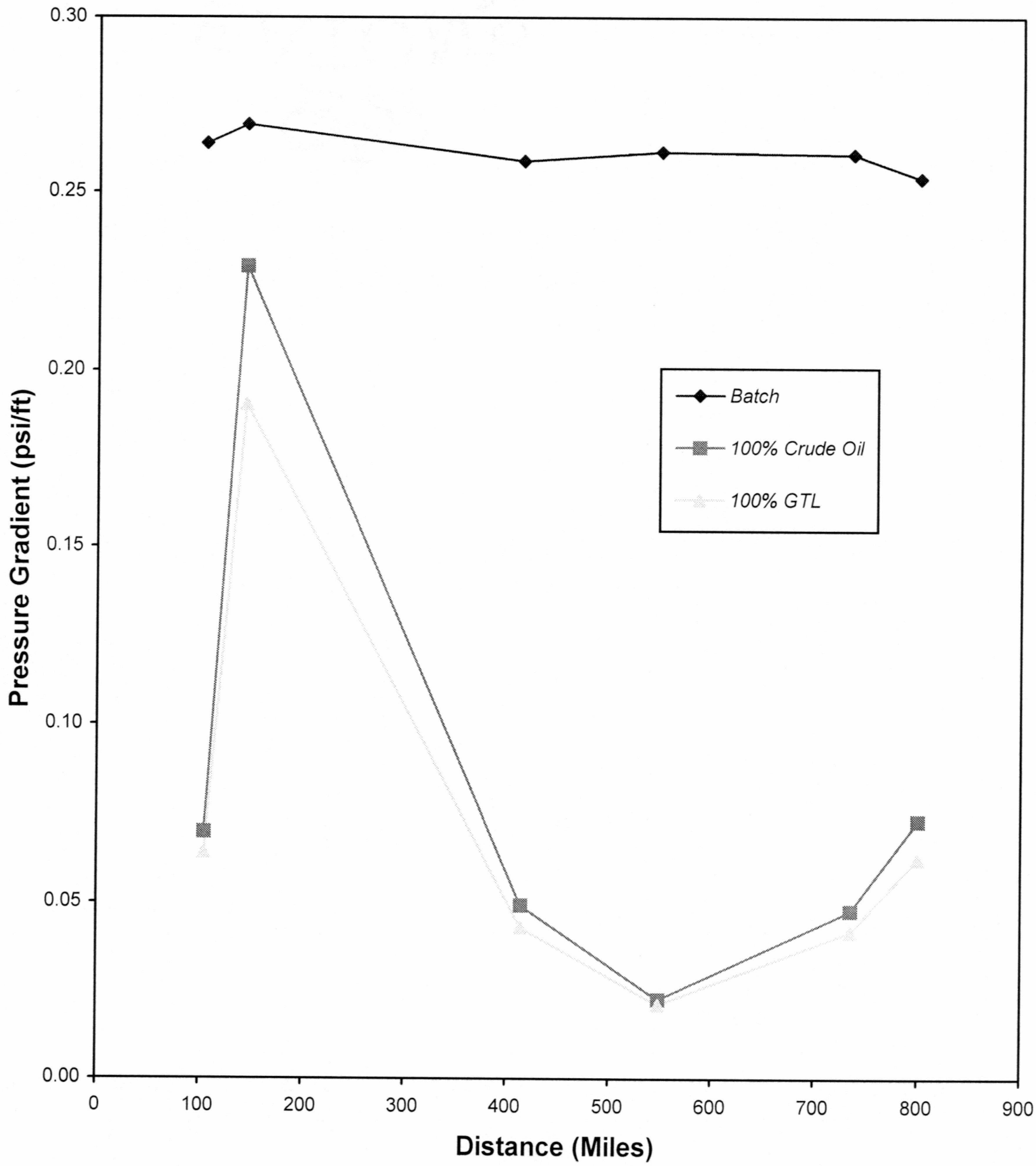
1. Based on the equations presented in this work, batch and commingled flow models can be analytically solved for predicting the pressure gradients encountered when considering the transport of GTL products and Crude Oil through the Trans-Alaskan Pipeline System (TAPS).

2. The derived flow equations presented here can be modified under specified operating conditions or constraints of the Trans-Alaskan Pipeline System (TAPS), using live GTL or Crude Oil data.

3. Mixing at the Oil-GTL interface in the case of batch mode transportation poses flow modeling and simulation difficulties.

4. The results of the sample calculation indicate that the pressure gradients obtained from the batch flow calculations are higher than those obtained from that of commingled flow. The reason being that for batch flow, the pressure gradient is the ratio of the total pressure drop across the slug to the slug length, whereas for commingled flow, it is the ratio of the total pressure drop to the length of the pipe segment. This has been graphically illustrated by **Figure 5.1**.

Figure 5.1 Comparison Plot of Batch and Commingled Flow Modes



5.2 RECOMMENDATIONS

For future work in this area, the following recommendations are being presented for consideration:

1. A complete economic analysis of the transportation modes should be carried out with a view of recommending a viable mode for transporting GTL products through the Trans-Alaskan Pipeline System (TAPS).

2. For the commingled flow model, it is important to select an optimal ratio for blending GTL products with Crude Oil. This is important, in that it affects the properties of the resulting fluid, and consequently, the results of any analysis carried out on the flow mode.

3. The effect of temperature, as it affects the fluid properties, should be studied for both transport modes. Since GTL has a low viscosity, the effect of temperature changes on the properties of the fluid is a very important factor that may cause the waxing of GTL products.

4. For the batch flow model, the effect of the interface zone as it passes through the pumps, is a very important factor for consideration. Since the fluid in this pipe does not completely fill the pipe diameter, this might cause the pumps to "*cavitate*".

5. Further studies on the interaction of GTL transport on the internal monitoring of corrosion and pigging are necessary, since GTL may interact with corrosion inhibitors.

NOMENCLATURE

A	cross-sectional area of the pipe, m^2 [ft^2]
C	correction factor for the liquid hold-up in the slug
C_e	constant in Euler's equation
C_o	film distribution parameter
D	pipe diameter, m [inch.]
D_f	hydraulic diameter occupied by the film, m [inch.]
E_{lf}	liquid holdup in the film
E_{ls}	liquid holdup in the slug
F_S	resultant of forces
f_f	friction factor for the interface zone based on R_{emz}
f_s	friction factor in the liquid slug based on R_{es}
g, g_c	acceleration due to gravity, 9.81 m/s^2 or 32.2 ft/s^2
h, z	height or elevation, m [ft]
h_f	head loss due to friction, m [ft]
Δh_p	pump head, m [ft]
k_m	factor for the length of the mixing zone
L	length or distance, m [ft]
l_m	length of the mixing zone, m [ft]
l_s	length of the slug, m [ft]
m_e	mass exchange rate, kg/s [lbm/s]
N_{R_e}	Reynolds number
ΔP	pressure drop, N/m^2 [psi]
ΔP_a	acceleration pressure drop, N/m^2 [psi]

ΔP_f	frictional pressure drop, N/m^2 [psi]
ΔP_h	hydrostatic pressure drop, N/m^2 [psi]
$\Delta P/L$	average pressure gradient, N/m^2 [psi]
R_{emz}	Reynolds number for the interface zone
R_{es}	Reynolds number for the liquid slug
V_d	drift velocity, m/s [ft/s]
V_f	Interface zone velocity, m/s [ft/s]
V_m	mixture velocity, m/s [ft/s]
V_s	average velocity of the slug, m/s [ft/s]
V_{sl}	superficial liquid velocity, m/s [ft/s]
V_t	transitional velocity, m/s [ft/s]
W_p	Liquid wetted perimeter of the pipe wall, m [inch]
X	Lockhart-Martinelli parameter
Δz	change in elevation , m [ft]
β	angle of inclination, °
ε	pipe roughness, m [ft]
μ_l	Liquid viscosity, cp.
μ_{mz}	Viscosity of the interface zone, cp.
ρ_l	liquid density, kg/m^3 [lb/gallon]
ρ_{mz}	Density of the interface zone, kg/m^3 [lb/gallon]
ω	slug frequency

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APPENDIX A

VISUAL BASIC CODE FOR THE MODEL EQUATIONS

The following is the code written for the model macro:

```
' Hydraulic Model Macro to Evaluate the Modes of Transporting GTL Products
' through the Trans-Alaska Pipeline System (TAPS)
'
'  Written by Chinedu Franklyn Akwukwaegbu as part of the MS thesis.
' This program can be used as part of the GTL Transportation Study, currently
' being carried out at the Petroleum Engineering Program, University of Alaska
' Fairbanks.

' Declaration statements
   ' Common Variables
Public Fluid_1_FlowRate, Fluid_2_FlowRate
Public Fluid_1_Nu, Fluid_2_Nu
Public Fluid_1_SG, Fluid_2_SG
Public Fluid_1_Rho_ppg, Fluid_1_Rho_lb
Public Fluid_2_Rho_ppg, Fluid_2_Rho_lb
Public Fluid_1_Temp
Public VSL_1, VSL_2
Public ELF, ELS, VF, VM, VT, V
Public LS, LM, DF, HR
Public DPL_1, DPL_2, DPL_3, DPL_4, DPL_5, DPL_6
   ' Constants
Public Const Pipe_D = 48            ' Pipe Diameter (inches)
Public Const D = Pipe_D / 12         ' Conversion from inches to feet
Public Const Pipe_Length = 800       ' Pipe Length (miles)
Public Const PipeRough = 0.00001     ' Pipe Roughness (ft)
Public Const Pi = 3.14159265
Public Const Fit_Loss1 = 50         ' Pressure drop through fittings in Pipe segment #1
Public Const Fit_Loss2 = 50         ' Pressure drop through fittings in Pipe segment #2
Public Const Fit_Loss3 = 50         ' Pressure drop through fittings in Pipe segment #3
Public Const Fit_Loss4 = 50         ' Pressure drop through fittings in Pipe segment #4
Public Const Fit_Loss5 = 50         ' Pressure drop through fittings in Pipe segment #5
Public Const Fit_Loss6 = 50         ' Pressure drop through fittings in Pipe segment #6

' DEFINITIONS OF THE VARIABLES DECLARED ABOVE
' Fluid_1_FlowRate, Fluid_2_FlowRate = Fluid Flow rates
' Fluid_1_Nu, Fluid_2_Nu = Fluid viscosities
' Fluid_1_SG, Fluid_2_SG = Fluid specific gravity
' Fluid_1_Rho_ppg, Fluid_2_Rho_ppg = Fluid Density (lb/gallon)
' Fluid_1_Rho_lb, Fluid_2_Rho_lb  = Fluid Density (lb/ft3)
' Fluid_1_Temp = Fluid Temperature
```

```
' VSL_1, VSL_2 = Fluid Superficial Velocities (Batch Flow)
' ELF, ELS = Liquid Holdup of Interface Zone and Slug respectively (Batch Flow)
' VM, VF = Velocities of Slug and Interface zone respectively (Batch Flow)
' VT = Slug transitional velocity (Batch flow)
' LS, LM  = Length of Slug and Interface zone respectively (Batch flow)
' DF = Pipe Diameter occupied by the Interface Zone
' HR = DF to Pipe Diameter Ratio
' DPL_1, DPL_2, DPL_3, DPL_4, DPL_5, DPL_6 = Pressure Gradients
```

Public Sub Batch_Flow()

```
' This is the Batch-Flow Calculation Sub-program

' Select the results worksheet
   Sheets("BatchFlow_Output").Select

' This is the calculation subroutine for the Batch Flow Model
   MsgBox "This is the Calculation Sheet for the Batch Flow Model."

' Input Data Collection
   BatchFlow_Input

' Computing the general fluid properties
      ' Superficial Velocities
   QL_1 = Range("C8")                    ' this is the Liquid flow rate in CFS
   VSL_1 = 4# * QL_1 / (Pi * (D) ^ 2)  ' First Liquid Superficial velocity
   QL_2 = Range("H8")                    ' this is the flow rate in CFS
   VSL_2 = 4# * QL_2 / (Pi * (D) ^ 2)  ' Second liquid Superficial velocity
   Range("C28").FormulaR1C1 = VSL_1
   Range("H28").FormulaR1C1 = VSL_2

      ' Compute the Mixture or Slug velocity
   VM = VSL_1 + VSL_2
   Range("C31").FormulaR1C1 = VM

      ' Compute the Transitional Velocity
   Temp = (32.2 * D * (Fluid_1_Rho_lb - Fluid_2_Rho_lb)) / Fluid_1_Rho_lb
   VT = 1.2 * VM + 0.345 * Sqr(Temp)
   Range("C34").FormulaR1C1 = VT

 ' Computing the slug properties
      ' Compute the liquid hold-up in the slug
  ' Lockhart-Martinelli Parameter, X
   Temp1 = VSL_2 * Fluid_2_Rho_lb * Fluid_1_Nu
   Temp2 = VSL_1 * Fluid_1_Rho_lb * Fluid_2_Nu
   X = ((Temp1 / Temp2) ^ 0.2) * (VSL_1 ^ 2 * Fluid_1_Rho_lb) / (VSL_2 ^ 2 * Fluid_2_Rho_lb)
   R = Log(X)     ' Correction Factor

      ' Theoretical Liquid Hold-up
   ELS_theo = Exp(-0.9304919 + 0.5285852 * R - 0.09219634 * R ^ 2 + 0.000902418 * R ^ 4)
   C = 0.528 * (VSL_1 * VSL_2) ^ -0.215121 ' Correction factor for turbulence
```

```
    ' Actual liquid hold-up in the slug
    ELS = C * ELS_theo

    ' Compute the length of the slug
    LS = Exp(-25.4144 + 28.4948 * ((Log(Pipe_D)) ^ 0.1))
    Range("C38").FormulaR1C1 = LS

    ' Compute the Length of the mixing zone
    LM = 30 * (1 - ELS) * D
    Range("C40").FormulaR1C1 = LM

    ' Compute the film velocity
    Slug_Freq = 0.0226 * (VSL_1 * (19.75 + VM ^ 2) * 12 / (32.2 * VM * D)) ^ 1.2
    VF = VM * (1 / (1 + 0.2 * VM / Slug_Freq))

    ' Compute liquid hold-up in the film
    ELF = ELS * (VT - VM) / (VT - VF)

    ' Initialize loop
    MsgBox "Enter A Height Ratio For The Mixing Zone (Ranging from 0.1 - 0.5) "

    HR = InputBox(" Please Input The Mixing Zone Height Ratio (HR) ")
    DF = HR * D

    ' Begin Pipe Segment calculations
    Batch_PipeSegment_1
    Batch_PipeSegment_2
    Batch_PipeSegment_3
    Batch_PipeSegment_4
    Batch_PipeSegment_5
    Batch_PipeSegment_6

    'Calculate Total Pressure Drop Gradient
    Total_DPL = DPL_1 + DPL_2 + DPL_3 + DPL_4 + DPL_5 + DPL_6
    Range("C152").FormulaR1C1 = Total_DPL

    ' Select the results worksheet
    Range("A1").Select

    ' Print out a copy of the calculations
    PrintResults = MsgBox(" Print A Copy of The Results?", vbYesNo)
    If PrintResults = vbYes Then
      Batch_PrintResults
    Else
      End
    End If
'
End Sub

Public Sub BatchFlow_Input()
'
' This subroutine handles the Input Data Collection
```

```
    MsgBox "Please enter the first fluid properties."

    Fluid_1_Name = InputBox("Please Enter The Name of The First Fluid")
' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
    Do
    Fluid_1_FlowRate = InputBox(" Fluid Flowrate (MMBPD) ")
        If Fluid_1_FlowRate <> "" Then
            If IsNumeric(Fluid_1_FlowRate) Then
                Exit Do
            Else
                CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
                If CheckForValidEntry = vbNo Then
                    MsgBox "The Macro Will Not Run."
                    End
                End If
            End If
        Else
            CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
            If CheckForEmptyEntry = vbNo Then
                MsgBox "The Macro Will Not Run."
                End
            End If
        End If
    Loop Until IsNumeric(Fluid_1_FlowRate)
' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
    Do
    Fluid_1_Temp = InputBox(" Fluid Temperature (F) ")
        If Fluid_1_Temp <> "" Then
            If IsNumeric(Fluid_1_Temp) Then
                Exit Do
            Else
                CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
                If CheckForValidEntry = vbNo Then
                    MsgBox "The Macro Will Not Run."
                    End
                End If
            End If
        Else
            CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
            If CheckForEmptyEntry = vbNo Then
                MsgBox "The Macro Will Not Run."
                End
            End If
        End If
    Loop Until IsNumeric(Fluid_1_Temp)
' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
    Do
    Fluid_1_Nu = InputBox(" Fluid Viscosity (cP) ")
        If Fluid_1_Nu <> "" Then
            If IsNumeric(Fluid_1_Nu) Then
                Exit Do
            Else
                CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
```

```
            If CheckForValidEntry = vbNo Then
                MsgBox "The Macro Will Not Run."
                End
            End If
        End If
    Else
        CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
        If CheckForEmptyEntry = vbNo Then
            MsgBox "The Macro Will Not Run."
            End
        End If
    End If
Loop Until IsNumeric(Fluid_1_Nu)
' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
Do
Fluid_1_SG = InputBox(" Fluid Specific Gravity ")
    If Fluid_1_SG <> "" Then
        If IsNumeric(Fluid_1_SG) Then
            Exit Do
        Else
            CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
            If CheckForValidEntry = vbNo Then
                MsgBox "The Macro Will Not Run."
                End
            End If
        End If
    Else
        CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
        If CheckForEmptyEntry = vbNo Then
            MsgBox "The Macro Will Not Run."
            End
        End If
    End If
Loop Until IsNumeric(Fluid_1_SG)
'
MsgBox "Please enter the second fluid properties."
'
Fluid_2_Name = InputBox("Please Enter The Name of The Second Fluid")
'
' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
Do
Fluid_2_FlowRate = InputBox(" Fluid Flowrate (MMBPD) ")
    If Fluid_2_FlowRate <> "" Then
        If IsNumeric(Fluid_2_FlowRate) Then
            Exit Do
        Else
            CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
            If CheckForValidEntry = vbNo Then
                MsgBox "The Macro Will Not Run."
                End
            End If
        End If
    Else
```

```
            CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
            If CheckForEmptyEntry = vbNo Then
              MsgBox "The Macro Will Not Run."
              End
            End If
          End If
        Loop Until IsNumeric(Fluid_2_FlowRate)
      ' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
        Do
        Fluid_2_Nu = InputBox(" Fluid Viscosity (cP) ")
          If Fluid_2_Nu <> "" Then
            If IsNumeric(Fluid_2_Nu) Then
              Exit Do
            Else
              CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
              If CheckForValidEntry = vbNo Then
                MsgBox "The Macro Will Not Run."
                End
              End If
            End If
          Else
            CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
            If CheckForEmptyEntry = vbNo Then
              MsgBox "The Macro Will Not Run."
              End
            End If
          End If
        Loop Until IsNumeric(Fluid_2_Nu)
      ' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
        Do
        Fluid_2_SG = InputBox(" Fluid Specific Gravity ")
          If Fluid_2_SG <> "" Then
            If IsNumeric(Fluid_2_SG) Then
              Exit Do
            Else
              CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
              If CheckForValidEntry = vbNo Then
                MsgBox "The Macro Will Not Run."
                End
              End If
            End If
          Else
            CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
            If CheckForEmptyEntry = vbNo Then
              MsgBox "The Macro Will Not Run."
              End
            End If
          End If
        Loop Until IsNumeric(Fluid_2_SG)

      ' Start of Calculation Path
        Fluid_1_FlowRate = Fluid_1_FlowRate * 1000000#  ' Converts from regular number
        Fluid_2_FlowRate = Fluid_2_FlowRate * 1000000# ' Converts from regular number
```

```
'Convert the specific gravity to relevant density units
    ' Liquid
    Fluid_1_Rho_ppg = Fluid_1_SG * 8.34   'Converts it to Pounds per gallon
    Fluid_1_Rho_lb = Fluid_1_SG * 62.371  'Converts it to Pounds per cubic feet
    ' Gas
    Fluid_2_Rho_ppg = Fluid_2_SG * 8.34   'Converts it to Pounds per gallon
    Fluid_2_Rho_lb = Fluid_2_SG * 62.371  'Converts it to Pounds per cubic feet

' Assign fluid & pipe properties to their respective spreadsheet cells
    Range("A6").FormulaR1C1 = Fluid_1_Name
    Range("F6").FormulaR1C1 = Fluid_2_Name
    Range("C7").FormulaR1C1 = Fluid_1_FlowRate
    Range("C10").FormulaR1C1 = Fluid_1_Nu
    Range("C12").FormulaR1C1 = Fluid_1_Rho_lb
    Range("H7").FormulaR1C1 = Fluid_2_FlowRate
    Range("H10").FormulaR1C1 = Fluid_2_Nu
    Range("H12").FormulaR1C1 = Fluid_2_Rho_lb
    Range("C15").FormulaR1C1 = Fluid_1_Temp
    Range("C19").FormulaR1C1 = Pipe_D
    Range("C20").FormulaR1C1 = Pipe_Length
'
End Sub

Sub Batch_PipeSegment_1()
' This subroutine handles all the batch flow computation for
' Pipe Segment #1 (PS #1 - PS#3)

' Segment Length
    L1 = Worksheets("PipeSegmentData").Cells(4, 4)

' Change in Elevation
    DZ1 = Worksheets("PipeSegmentData").Cells(4, 5)

' Compute the Reynolds Number and friction factor for the mixing zone
    Rho_film_1 = Rho_Mix(ELF)
    Nu_film_1 = Nu_Mix(ELF)
    NREF_1 = Reynolds_Number(DF, VF, Rho_film_1, Nu_film_1)
    film_fric_1 = Friction(NREF_1)

' Compute the Reynolds Number and friction factor for the slug
    NRES_1 = Reynolds_Number(D, VM, Fluid_1_Rho_ppg, Fluid_1_Nu)
    slug_fric_1 = Friction(NRES_1)

        ' Calculating the different pressure drops acting across a slug
' Pressure Drop Due to Friction
    DPF_S_1 = slug_fric_1 * Fluid_1_SG * (VM ^ 2) * LS / D             ' slug
    DPF_F_1 = film_fric_1 * (Rho_film_1 / 8.34) * (VF ^ 2) * LM / DF   ' film
' Total pressure drop due to friction
    DPF_1 = (DPF_S_1 + DPF_F_1) * 3.12235          ' Convert to Psi
    Range("C52").FormulaR1C1 = DPF_1

'Pressure drop due to Acceleration
```

```
    DPA_1 = Fluid_1_SG * ELS * (VT - VM) * (VM - VF) * 1.56118
    Range("C54").FormulaR1C1 = DPA_1

  ' Pressure drop due to hydrostatics
    DPH_1 = 0.17068 * (Fluid_1_Rho_ppg * LS + Rho_film_1 * LM) * DZ1 / L1
    Range("C56").FormulaR1C1 = DPH_1

  ' Total pressure drop across the slug
    DPT_1 = DPF_1 + DPA_1 + DPH_1
    Range("C58").FormulaR1C1 = DPT_1

  ' Pressure gradient
    DPL_1 = DPT_1 / LS
    Range("C60").FormulaR1C1 = DPL_1
  '
End Sub

Sub Batch_PipeSegment_2()
' This subroutine handles all the batch flow computation for
' Pipe Segment #2 (PS #3 - PS#4)

' Segment Length
   L2 = Worksheets("PipeSegmentData").Cells(5, 4)

' Change in Elevation
   DZ2 = Worksheets("PipeSegmentData").Cells(5, 5)

' Compute the Reynolds Number and friction factor for the mixing zone
   Rho_film_2 = Rho_Mix(ELF)
   Nu_film_2 = Nu_Mix(ELF)
   NREF_2 = Reynolds_Number(DF, VF, Rho_film_2, Nu_film_2)
   film_fric_2 = Friction(NREF_2)

' Compute the Reynolds Number and friction factor for the slug
   NRES_2 = Reynolds_Number(D, VM, Fluid_1_Rho_ppg, Fluid_1_Nu)
   slug_fric_2 = Friction(NRES_2)

      ' Calculating the different pressure drops acting across a slug
' Pressure Drop Due to Friction
   DPF_S_2 = slug_fric_2 * Fluid_1_SG * (VM ^ 2) * LS / D          ' slug
   DPF_F_2 = film_fric_2 * (Rho_film_2 / 8.34) * (VF ^ 2) * LM / DF   ' film
' Total pressure drop due to friction
   DPF_2 = (DPF_S_2 + DPF_F_2) * 3.12235          ' Convert to Psi
   Range("C70").FormulaR1C1 = DPF_2

'Pressure drop due to Acceleration
   DPA_2 = Fluid_1_SG * ELS * (VT - VM) * (VM - VF) * 1.56118
   Range("C72").FormulaR1C1 = DPA_2

' Pressure drop due to hydrostatics
   DPH_2 = 0.17068 * (Fluid_1_Rho_ppg * LS + Rho_film_2 * LM) * DZ2 / L2
   Range("C74").FormulaR1C1 = DPH_2
```

```
' Total pressure drop across the slug
  DPT_2 = DPF_2 + DPA_2 + DPH_2
  Range("C76").FormulaR1C1 = DPT_2

' Pressure gradient per effective slug length
  DPL_2 = DPT_2 / LS
  Range("C78").FormulaR1C1 = DPL_2
'
End Sub

Sub Batch_PipeSegment_3()
' This subroutine handles all the batch flow computation for
' Pipe Segment #3 (PS #4 - PS#7)

' Segment Length
  L3 = Worksheets("PipeSegmentData").Cells(6, 4)

' Change in Elevation
  DZ3 = Worksheets("PipeSegmentData").Cells(6, 5)

' Compute the Reynolds Number and friction factor for the mixing zone
  Rho_film_3 = Rho_Mix(ELF)
  Nu_film_3 = Nu_Mix(ELF)
  NREF_3 = Reynolds_Number(DF, VF, Rho_film_3, Nu_film_3)
  film_fric_3 = Friction(NREF_3)

' Compute the Reynolds Number and friction factor for the slug
  NRES_3 = Reynolds_Number(D, VM, Fluid_1_Rho_ppg, Fluid_1_Nu)
  slug_fric_3 = Friction(NRES_3)

     ' Calculating the different pressure drops acting across a slug
' Pressure Drop Due to Friction
  DPF_S_3 = slug_fric_3 * Fluid_1_SG * (VM ^ 2) * LS / D          ' slug
  DPF_F_3 = film_fric_3 * (Rho_film_3 / 8.34) * (VF ^ 2) * LM / DF  ' film
' Total pressure drop due to friction
  DPF_3 = (DPF_S_3 + DPF_F_3) * 3.12235           ' Convert to Psi
  Range("C88").FormulaR1C1 = DPF_3

'Pressure drop due to Acceleration
  DPA_3 = Fluid_1_SG * ELS * (VT - VM) * (VM - VF) * 1.56118
  Range("C90").FormulaR1C1 = DPA_3

' Pressure drop due to hydrostatics
  DPH_3 = 0.17068 * (Fluid_1_Rho_ppg * LS + Rho_film_3 * LM) * DZ3 / L3
  Range("C92").FormulaR1C1 = DPH_3

' Total pressure drop across the slug
  DPT_3 = DPF_3 + DPA_3 + DPH_3
  Range("C94").FormulaR1C1 = DPT_3

' Pressure gradient
  DPL_3 = DPT_3 / LS
  Range("C96").FormulaR1C1 = DPL_3
```

```
'
End Sub

Sub Batch_PipeSegment_4()
' This subroutine handles all the batch flow computation for
' Pipe Segment #4 (PS #7 - PS#9)

' Segment Length
  L4 = Worksheets("PipeSegmentData").Cells(7, 4)

' Change in Elevation
  DZ4 = Worksheets("PipeSegmentData").Cells(7, 5)

' Compute the Reynolds Number and friction factor for the mixing zone
  Rho_film_4 = Rho_Mix(ELF)
  Nu_film_4 = Nu_Mix(ELF)
  NREF_4 = Reynolds_Number(DF, VF, Rho_film_4, Nu_film_4)
  film_fric_4 = Friction(NREF_4)

' Compute the Reynolds Number and friction factor for the slug
  NRES_4 = Reynolds_Number(D, VM, Fluid_1_Rho_ppg, Fluid_1_Nu)
  slug_fric_4 = Friction(NRES_4)

     ' Calculating the different pressure drops acting across a slug
' Pressure Drop Due to Friction
  DPF_S_4 = slug_fric_4 * Fluid_1_SG * (VM ^ 2) * LS / D          ' slug
  DPF_F_4 = film_fric_4 * (Rho_film_4 / 8.34) * (VF ^ 2) * LM / DF   ' film
' Total pressure drop due to friction
  DPF_4 = (DPF_S_4 + DPF_F_4) * 3.12235          ' Convert to Psi
  Range("C103").FormulaR1C1 = DPF_4

'Pressure drop due to Acceleration
  DPA_4 = Fluid_1_SG * ELS * (VT - VM) * (VM - VF) * 1.56118
  Range("C105").FormulaR1C1 = DPA_4

' Pressure drop due to hydrostatics
  DPH_4 = 0.17068 * (Fluid_1_Rho_ppg * LS + Rho_film_4 * LM) * DZ4 / L4
  Range("C107").FormulaR1C1 = DPH_4

' Total pressure drop across the slug
  DPT_4 = DPF_4 + DPA_4 + DPH_4
  Range("C109").FormulaR1C1 = DPT_4

' Pressure gradient
  DPL_4 = DPT_4 / LS
  Range("C111").FormulaR1C1 = DPL_4
'
End Sub

Sub Batch_PipeSegment_5()
' This subroutine handles all the batch flow computation for
' Pipe Segment #5 (PS #9 - PS#12)
```

```
' Segment Length
   L5 = Worksheets("PipeSegmentData").Cells(8, 4)

' Change in Elevation
   DZ5 = Worksheets("PipeSegmentData").Cells(8, 5)

' Compute the Reynolds Number and friction factor for the mixing zone
   Rho_film_5 = Rho_Mix(ELF)
   Nu_film_5 = Nu_Mix(ELF)
   NREF_5 = Reynolds_Number(DF, VF, Rho_film_5, Nu_film_5)
   film_fric_5 = Friction(NREF_5)

' Compute the Reynolds Number and friction factor for the slug
   NRES_5 = Reynolds_Number(D, VM, Fluid_1_Rho_ppg, Fluid_1_Nu)
   slug_fric_5 = Friction(NRES_5)

      ' Calculating the different pressure drops acting across a slug
' Pressure Drop Due to Friction
   DPF_S_5 = slug_fric_5 * Fluid_1_SG * (VM ^ 2) * LS / D            ' slug
   DPF_F_5 = film_fric_5 * (Rho_film_5 / 8.34) * (VF ^ 2) * LM / DF   ' film
' Total pressure drop due to friction
   DPF_5 = (DPF_S_5 + DPF_F_5) * 3.12235            ' Convert to Psi
   Range("C121").FormulaR1C1 = DPF_5

'Pressure drop due to Acceleration
   DPA_5 = Fluid_1_SG * ELS * (VT - VM) * (VM - VF) * 1.56118
   Range("C123").FormulaR1C1 = DPA_5

' Pressure drop due to hydrostatics
   DPH_5 = 0.17068 * (Fluid_1_Rho_ppg * LS + Rho_film_5 * LM) * DZ5 / L5
   Range("C125").FormulaR1C1 = DPH_5

' Total pressure drop across the slug
   DPT_5 = DPF_5 + DPA_5 + DPH_5
   Range("C127").FormulaR1C1 = DPT_5

' Pressure gradient
   DPL_5 = DPT_5 / LS
   Range("C129").FormulaR1C1 = DPL_5
'
End Sub

Sub Batch_PipeSegment_6()
' This subroutine handles all the batch flow computation for
' Pipe Segment #6 (PS #12 - Valdez)

' Segment Length
   L6 = Worksheets("PipeSegmentData").Cells(9, 4)

' Change in Elevation
   DZ6 = Worksheets("PipeSegmentData").Cells(9, 5)

' Compute the Reynolds Number and friction factor for the mixing zone
```

```
    Rho_film_6 = Rho_Mix(ELF)
    Nu_film_6 = Nu_Mix(ELF)
    NREF_6 = Reynolds_Number(DF, VF, Rho_film_6, Nu_film_6)
    film_fric_6 = Friction(NREF_6)

  ' Compute the Reynolds Number and friction factor for the slug
    NRES_6 = Reynolds_Number(D, VM, Fluid_1_Rho_ppg, Fluid_1_Nu)
    slug_fric_6 = Friction(NRES_6)

       ' Calculating the different pressure drops acting across a slug
  ' Pressure Drop Due to Friction
    DPF_S_6 = slug_fric_6 * Fluid_1_SG * (VM ^ 2) * LS / D          ' slug
    DPF_F_6 = film_fric_6 * (Rho_film_6 / 8.34) * (VF ^ 2) * LM / DF   ' film
  ' Total pressure drop due to friction
    DPF_6 = (DPF_S_6 + DPF_F_6) * 3.12235             ' Convert to Psi
    Range("C139").FormulaR1C1 = DPF_6

  'Pressure drop due to Acceleration
    DPA_6 = Fluid_1_SG * ELS * (VT - VM) * (VM - VF) * 1.56118
    Range("C141").FormulaR1C1 = DPA_6

  ' Pressure drop due to hydrostatics
    DPH_6 = 0.17068 * (Fluid_1_Rho_ppg * LS + Rho_film_6 * LM) * DZ6 / L6
    Range("C143").FormulaR1C1 = DPH_6

  ' Total pressure drop across the slug
    DPT_6 = DPF_6 + DPA_6 + DPH_6
    Range("C145").FormulaR1C1 = DPT_6

  ' Pressure gradient
    DPL_6 = DPT_6 / LS
    Range("C147").FormulaR1C1 = DPL_6
'
End Sub


Public Sub Commingled_Flow()
' Select the results worksheet
    Sheets("CommFlow_Output").Select

'This is the calculation subroutine for the Commingled flow model
    MsgBox "This is the Calculation Sheet for the Commingled Flow Model."

' Input Data Collection
    CommingledFlow_Input

' Calculate Pipe Flow Velocity
    Q = Range("C7")        ' this is the flow rate in CFS
    V = 4# * Q / (3.142 * (D) ^ 2)
    Range("C9").FormulaR1C1 = V

'Begin Segment Calculations
    Commingled_PipeSegment_1
```

```
    Commingled_PipeSegment_2
    Commingled_PipeSegment_3
    Commingled_PipeSegment_4
    Commingled_PipeSegment_5
    Commingled_PipeSegment_6

'Calculate Total Pressure Drop Gradient
    Total_DPL = DPL_1 + DPL_2 + DPL_3 + DPL_4 + DPL_5 + DPL_6
    Range("C126").FormulaR1C1 = Total_DPL

' Select the results worksheet
    Range("A1").Select

' Print out a copy of the calculations
    PrintResults = MsgBox(" Print A Copy of The Results?", vbYesNo)
    If PrintResults = vbYes Then
        Batch_PrintResults
    End If

' Check to see if user needs to re-run calculations
    ReCheck = MsgBox("Do You Want To Re-Run The Calculations Again?", vbYesNo)
    If ReCheck = vbYes Then
      Commingled_Flow
    Else
        End
    End If
'
End Sub

Public Sub CommingledFlow_Input()
' This subroutine handles the Input Data Collection

    MsgBox "Please enter the liquid properties."

' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
    Do
    Fluid_1_FlowRate = InputBox(" Fluid Flowrate (MMBPD) ")
        If Fluid_1_FlowRate <> "" Then
            If IsNumeric(Fluid_1_FlowRate) Then
                Exit Do
            Else
                CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
                If CheckForValidEntry = vbNo Then
                    MsgBox "The Macro Will Not Run."
                    End
                End If
            End If
        Else
            CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
            If CheckForEmptyEntry = vbNo Then
                MsgBox "The Macro Will Not Run."
                End
            End If
```

```
    End If
  Loop Until IsNumeric(Fluid_1_FlowRate)
' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
  Do
  Fluid_1_Temp = InputBox(" Fluid Temperature (F) ")
    If Fluid_1_Temp <> "" Then
      If IsNumeric(Fluid_1_Temp) Then
        Exit Do
      Else
        CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
        If CheckForValidEntry = vbNo Then
          MsgBox "The Macro Will Not Run."
          End
        End If
      End If
    Else
      CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
      If CheckForEmptyEntry = vbNo Then
        MsgBox "The Macro Will Not Run."
        End
      End If
    End If
  Loop Until IsNumeric(Fluid_1_Temp)
' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
  Do
  Fluid_1_Nu = InputBox(" Fluid Viscosity (cP) ")
    If Fluid_1_Nu <> "" Then
      If IsNumeric(Fluid_1_Nu) Then
        Exit Do
      Else
        CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
        If CheckForValidEntry = vbNo Then
          MsgBox "The Macro Will Not Run."
          End
        End If
      End If
    Else
      CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
      If CheckForEmptyEntry = vbNo Then
        MsgBox "The Macro Will Not Run."
        End
      End If
    End If
  Loop Until IsNumeric(Fluid_1_Nu)
' Nested "If" & "Do" Loop To Ensure That A Valid Input is obtained from the user
  Do
  Fluid_1_SG = InputBox(" Fluid Specific Gravity ")
    If Fluid_1_SG <> "" Then
      If IsNumeric(Fluid_1_SG) Then
        Exit Do
      Else
        CheckForValidEntry = MsgBox("No Value Entered. Do You Want To Enter Again?", vbYesNo)
        If CheckForValidEntry = vbNo Then
```

```
                MsgBox "The Macro Will Not Run."
                End
            End If
        End If
    Else
        CheckForEmptyEntry = MsgBox("No Data Entered. Do You Want To Enter Again?", vbYesNo)
        If CheckForEmptyEntry = vbNo Then
            MsgBox "The Macro Will Not Run."
            End
        End If
    End If
  Loop Until IsNumeric(Fluid_1_SG)

' Start of Calculation Path
  Fluid_1_FlowRate = Fluid_1_FlowRate * 1000000#  ' Converts from regular number

'Convert the specific gravity to relevant density units
  Fluid_1_Rho_ppg = Fluid_1_SG * 8.34   'Converts it to Pounds per gallon
  Fluid_1_Rho_lb = Fluid_1_SG * 62.371  'Converts it to Pounds per cubic feet

'Assign fluid & pipe properties to their respective cells
  Range("C6").FormulaR1C1 = Fluid_1_FlowRate
  Range("C11").FormulaR1C1 = Fluid_1_Nu
  Range("C13").FormulaR1C1 = Fluid_1_Rho_lb
  Range("C15").FormulaR1C1 = Fluid_1_Temp
  Range("C17").FormulaR1C1 = Pipe_D
  Range("C18").FormulaR1C1 = Pipe_Length
  Range("C19").FormulaR1C1 = PipeRough
'
End Sub

Sub Commingled_PipeSegment_1()
' This subroutine handles all the commingled flow computation for
' Pipe Segment #1 (PS #1 - PS#3)

' Segment Length
  L1 = Worksheets("PipeSegmentData").Cells(4, 4)

' Change in Elevation
  DZ1 = Worksheets("PipeSegmentData").Cells(4, 5)

' Calculate the Reynolds Number
  NRE = Reynolds_Number(D, V, Fluid_1_Rho_ppg, Fluid_1_Nu)

'Calculate the friction factor as a function of the Reynolds Number;
  f_fac = Friction(NRE)

' Calculate the head loss due to friction
  Head_fl = 4 * f_fac * L1 * (V ^ 2) / (2 * 32.2 * (D))

'       Evaluate the head supplied by the pumps.
' This involves the utilization of the "Pump Data" worksheet provided by Alyeska
' Pipeline Service Company. It calculates the head provided by the pumps as a function
```

```
' of the fluid throughput.
' Input is the flow rate & the required output is the actual head provided by the pumps

' Input the flow rate
    Q1 = Fluid_1_FlowRate / 2#
    Worksheets("PumpData").Cells(5, 2) = Q1

' Obtain the calculated head
    Pump_Head = Worksheets("PumpData").Cells(27, 2)
    Pump_Head1 = 2# * Pump_Head

'Determine Pressure losses through the check valves & other fittings
    Loss_Fit1 = Worksheets("PipeSegmentData").Cells(18, 3) + Fit_Loss1

' Evaluate the pressure drop due to flow
    DP1 = (Fluid_1_Rho_lb * 32.2 * (Pump_Head1 - (DZ1 + Head_f1)) / 144#) + Loss_Fit1

'Calculate the Pressure Gradient
    DPL_1 = DP1 / L1

'Display results
    Range("C30").FormulaR1C1 = Head_f1
    Range("C32").FormulaR1C1 = Loss_Fit1
    Range("C34").FormulaR1C1 = Pump_Head1
    Range("C36").FormulaR1C1 = DPL_1
'
End Sub

Sub Commingled_PipeSegment_2()
' This subroutine handles all the computation for Pipe Segment #2
' (PS #3 - PS#4)

' Segment Length
    L2 = Worksheets("PipeSegmentData").Cells(5, 4)

' Change in Elevation
    DZ2 = Worksheets("PipeSegmentData").Cells(5, 5)

' Calculate the Reynolds Number
    NRE = Reynolds_Number(Pipe_D, V, Fluid_1_Rho_ppg, Fluid_1_Nu)

'Calculate the friction factor as a function of the Reynolds Number;
    f_fac = Friction(NRE)

' Calculate the head loss due to friction
    Head_f2 = 4 * f_fac * L2 * (V ^ 2) / (2 * 32.2 * (D))

'        Evaluate the head supplied by the pumps.
' This involves the utilization of the "Pump Data" worksheet provided by Alyeska
' Pipeline Service Company. It calculates the head provided by the pumps as a function
' of the fluid throughput.
' Input is the flow rate & the required output is the actual head provided by the pumps
```

```
' Input the flow rate
   Q2 = Fluid_1_FlowRate / 2#
   Worksheets("PumpData").Cells(5, 2) = Q2

' Obtain the calculated head
   Pump_Head = Worksheets("PumpData").Cells(27, 2)
   Pump_Head2 = 2 * Pump_Head

'Determine Pressure losses through the check valves & other fittings
   Loss_Fit2 = Worksheets("PipeSegmentData").Cells(19, 3) + Fit_Loss2

' Evaluate the pressure drop due to flow
   DP2 = (Fluid_1_Rho_lb * 32.2 * (Pump_Head2 - (DZ2 + Head_f2)) / 144#) + Loss_Fit2

'Calculate the Pressure Gradient
   DPL_2 = DP2 / L2

'Display results
   Range("C45").FormulaR1C1 = Head_f2
   Range("C47").FormulaR1C1 = Loss_Fit2
   Range("C49").FormulaR1C1 = Pump_Head2
   Range("C51").FormulaR1C1 = DPL_2
'
End Sub

Sub Commingled_PipeSegment_3()
' This subroutine handles all the computation for Pipe Segment #3
' (PS #4 - PS#7)

' Segment Length
   L3 = Worksheets("PipeSegmentData").Cells(6, 4)

' Change in Elevation
   DZ3 = Worksheets("PipeSegmentData").Cells(6, 5)

' Calculate the Reynolds Number
   NRE = Reynolds_Number(Pipe_D, V, Fluid_1_Rho_ppg, Fluid_1_Nu)

'Calculate the friction factor as a function of the Reynolds Number;
   f_fac = Friction(NRE)

' Calculate the head loss due to friction
   Head_f3 = 4 * f_fac * L3 * (V ^ 2) / (2 * 32.2 * (D))

'        Evaluate the head supplied by the pumps.
' This involves the utilization of the "Pump Data" worksheet provided by Alyeska
' Pipeline Service Company. It calculates the head provided by the pumps as a function
' of the fluid throughput.
' Input is the flow rate & the required output is the actual head provided by the pumps

' Input the flow rate
   Q3 = Fluid_1_FlowRate / 2#
   Worksheets("PumpData").Cells(5, 2) = Q3
```

```
' Obtain the calculated head
   Pump_Head = Worksheets("PumpData").Cells(27, 2)
   Pump_Head3 = 2# * Pump_Head

'Determine Pressure losses through the check valves & other fittings
   Loss_Fit3 = Worksheets("PipeSegmentData").Cells(20, 3) + Fit_Loss3

' Evaluate the pressure drop due to flow
   DP3 = (Fluid_1_Rho_lb * 32.2 * (Pump_Head3 - (DZ3 + Head_f3)) / 144#) + Loss_Fit3

'Calculate the Pressure Gradient
   DPL_3 = DP3 / L3

'Display results
   Range("C59").FormulaR1C1 = Head_f3
   Range("C61").FormulaR1C1 = Loss_Fit3
   Range("C63").FormulaR1C1 = Pump_Head3
   Range("C65").FormulaR1C1 = DPL_3
'
End Sub

Sub Commingled_PipeSegment_4()
' This subroutine handles all the computation for Pipe Segment #4
' (PS #7 - PS#9)

' Segment Length
   L4 = Worksheets("PipeSegmentData").Cells(7, 4)

' Change in Elevation
   DZ4 = Worksheets("PipeSegmentData").Cells(7, 5)

' Calculate the Reynolds Number
   NRE = Reynolds_Number(Pipe_D, V, Fluid_1_Rho_ppg, Fluid_1_Nu)

'Calculate the friction factor as a function of the Reynolds Number;
   f_fac = Friction(NRE)

' Calculate the head loss due to friction
   Head_f4 = 4 * f_fac * L4 * (V ^ 2) / (2 * 32.2 * (D))

'        Evaluate the head supplied by the pumps.
' This involves the utilization of the "Pump Data" worksheet provided by Alyeska
' Pipeline Service Company. It calculates the head provided by the pumps as a function
' of the fluid throughput.
' Input is the flow rate & the output is the actual head provided by the pumps

' Input the flow rate
   Q4 = Fluid_1_FlowRate / 2
   Worksheets("PumpData").Cells(5, 4) = Q4

' Obtain the calculated head
   Pump_Head = Worksheets("PumpData").Cells(27, 4)
```

```
   Pump_Head4 = Pump_Head * 2

'Determine Pressure losses through the check valves & other fittings
   Loss_Fit4 = Worksheets("PipeSegmentData").Cells(21, 3) + Fit_Loss4

' Evaluate the pressure drop due to flow
   DP4 = (Fluid_1_Rho_lb * 32.2 * (Pump_Head4 - (DZ4 + Head_f4)) / 144#) + Loss_Fit4

'Calculate the Pressure Gradient
   DPL_4 = DP4 / L4

'Display results
   Range("C77").FormulaR1C1 = Head_f4
   Range("C79").FormulaR1C1 = Loss_Fit4
   Range("C81").FormulaR1C1 = Pump_Head4
   Range("C83").FormulaR1C1 = DPL_4
'
End Sub

Sub Commingled_PipeSegment_5()
' This subroutine handles all the computation for Pipe Segment #5
' (PS #9 - PS#12)

' Segment Length
   L5 = Worksheets("PipeSegmentData").Cells(8, 4)

' Change in Elevation
   DZ5 = Worksheets("PipeSegmentData").Cells(8, 5)

' Calculate the Reynolds Number
   NRE = Reynolds_Number(Pipe_D, V, Fluid_1_Rho_ppg, Fluid_1_Nu)

'Calculate the friction factor as a function of the Reynolds Number;
   f_fac = Friction(NRE)

' Calculate the head loss due to friction
   Head_f5 = 4 * f_fac * L5 * (V ^ 2) / (2 * 32.2 * (D))

'         Evaluate the head supplied by the pumps.
' This involves the utilization of the "Pump Data" worksheet provided by Alyeska
' Pipeline Service Company. It calculates the head provided by the pumps as a function
' of the fluid throughput.
' Input is the flow rate & the output is the actual head provided by the pumps

' Input the flow rate
   Q5 = Fluid_1_FlowRate / 2#
   Worksheets("PumpData").Cells(5, 3) = Q5

' Obtain the calculated head
   Pump_Head = Worksheets("PumpData").Cells(27, 3)
   Pump_Head5 = 2# * Pump_Head

'Determine Pressure losses through the check valves & other fittings
```

```
   Loss_Fit5 = Worksheets("PipeSegmentData").Cells(22, 3) + Fit_Loss5

' Evaluate the pressure drop due to flow
   DP5 = (Fluid_1_Rho_lb * 32.2 * (Pump_Head5 - (DZ5 + Head_f5)) / 144#) + Loss_Fit5

'Calculate the Pressure Gradient
   DPL_5 = DP5 / L5

'Display results
   Range("C95").FormulaR1C1 = Head_f5
   Range("C97").FormulaR1C1 = Loss_Fit5
   Range("C99").FormulaR1C1 = Pump_Head5
   Range("C101").FormulaR1C1 = DPL_5
'
End Sub

Sub Commingled_PipeSegment_6()
' This subroutine handles all the computation for Pipe Segment #6
' (PS #12 - Valdez)

' Segment Length
   L6 = Worksheets("PipeSegmentData").Cells(9, 4)

' Change in Elevation
   DZ6 = Worksheets("PipeSegmentData").Cells(9, 5)

' Calculate the Reynolds Number
   NRE = Reynolds_Number(Pipe_D, V, Fluid_1_Rho_ppg, Fluid_1_Nu)

'Calculate the friction factor as a function of the Reynolds Number;
   f_fac = Friction(NRE)

' Calculate the head loss due to friction
   Head_f6 = 4 * f_fac * L6 * (V ^ 2) / (2 * 32.2 * (D))

'        Evaluate the head supplied by the pumps.
' This involves the utilization of the "Pump Data" worksheet provided by Alyeska
' Pipeline Service Company. It calculates the head provided by the pumps as a function
' of the fluid throughput.
' Input is the flow rate & the output is the actual head provided by the pumps

' Input the flow rate
   Q6 = Fluid_1_FlowRate
   Worksheets("PumpData").Cells(5, 3) = Q6

' Obtain the calculated head
   Pump_Head = Worksheets("PumpData").Cells(27, 3)
   Pump_Head6 = Pump_Head

'Determine Pressure losses through the check valves & other fittings
   Loss_Fit6 = Worksheets("PipeSegmentData").Cells(23, 3) + Fit_Loss6

' Evaluate the pressure drop due to flow
```

```
   DP6 = (Fluid_1_Rho_lb * 32.2 * (Pump_Head6 - (DZ6 + Head_f6)) / 144#) + Loss_Fit6

'Calculate the Pressure Gradient
   DPL_6 = DP6 / L6

'Display results
   Range("C112").FormulaR1C1 = Head_f6
   Range("C114").FormulaR1C1 = Loss_Fit6
   Range("C116").FormulaR1C1 = Pump_Head6
   Range("C118").FormulaR1C1 = DPL_6
'
End Sub

Function Reynolds_Number(D, V, Rho, Nu)
'
' This function computes the Reynolds number
'
   Reynolds_Number = 928 * Rho * V * D * 12 / Nu
'
End Function

Function Friction(RE)
'
' This function computes the friction factor as a function of the Reynolds Number
'
   If RE <= 2100 Then
      Friction = 64 / RE
   Else
      Friction = Frict_Turb(RE)
   End If
'
End Function

Function Frict_Turb(RE)
'
' This function computes the turbulent friction factor
' (from the Zigrang & Sylvester Equation:- Nre > 2100)
'
   a1 = (PipeRough * 12 / D) / 3.7
   b1 = Log(a1 + 13 / RE)
   c1 = -2 * Log(a1 - (5.02 * b1 / RE))
   Frict_Turb = (1 / c1) ^ 2
'
End Function

Function Rho_Mix(HUP)
'
' Computes the density of the mixture
'
   Rho_Mix = Fluid_1_Rho_ppg * HUP + (1 - HUP) * Fluid_2_Rho_ppg
'
End Function
```

```
Function Nu_Mix(HUP)
'
' Computes the viscosity of the mixture
'
   Nu_Mix = Fluid_1_Nu * HUP + (1 - HUP) * Fluid_2_Nu
'
End Function

Sub Commingled_PrintResults()
'
' This subroutine prints out the calculation results for Commingled Flow
'
' Select the results worksheet
   Sheets("CommFlow_Output").Select
'
' Select cells
   Range("A1:H127").Select
   ActiveSheet.PageSetup.PrintArea = "$A$1:$H$127"
   ActiveWindow.SelectedSheets.PrintOut Copies:=1, Collate:=True

' Select the results worksheet
   Range("A1").Select
'
End Sub

Sub Batch_PrintResults()
'
' This subroutine prints out the calculation results for Batch Flow
'
' Select the results worksheet
   Sheets("BatchFlow_Output").Select
'
' Select cells
   Range("A1:H152").Select
   ActiveSheet.PageSetup.PrintArea = "$A$1:$H$152"
   ActiveWindow.SelectedSheets.PrintOut Copies:=1, Collate:=True

' Select the results worksheet
   Range("A1").Select
'
End Sub
```